Chapter

13

Transducers

INTRODUCTION 13.1

A transducer is defined as a device that receives energy from one system and transmits it to another, often in a different form.

Broadly defined, the transducer is a device capable of being actuated by an energising input from one or more transmission media and in turn generating a related signal to one or more transmission systems. It provides a usable output in response to a specified input measurand, which may be a physical or mechanical quantity, property, or conditions. The energy transmitted by these systems may be electrical, mechanical or acoustical.

The nature of electrical output from the transducer depends on the basic principle involved in the design. The output may be analog, digital or frequency modulated.

Basically, there are two types of transducers, electrical, and mechanical.

ELECTRICAL TRANSDUCER 13.2

An electrical transducer is a sensing device by which the physical, mechanical or optical quantity to be measured is transformed directly by a suitable mechanism into an electrical voltage/current proportional to the input measurand.

An electrical transducer must have the following parameters:

1. ***Linearity*** The relationship between a physical parameter and the resulting electrical signal must be linear.
2. ***Sensitivity*** This is defined as the electrical output per unit change in the physical parameter (for example V/°C for a temperature sensor). High sensitivity is generally desirable for a transducer.
3. ***Dynamic Range*** The operating range of the transducer should be wide, to permit its use under a wide range of measurement conditions.
4. ***Repeatability*** The input/output relationship for a transducer should be predictable over a long period of time. This ensures reliability of operation.
5. ***Physical Size*** The transducer must have minimal weight and volume, so that its presence in the measurement system does not disturb the existing conditions.

Advantages of Electrical Transducers The main advantages of electrical transducers (conversion of physical quantity into electrical quantities) are as follows:

1. Electrical amplification and attenuation can be easily done.
2. Mass-inertia effects are minimised.
3. Effects of friction are minimised.
4. The output can be indicated and recorded remotely at a distance from the sensing medium.
5. The output can be modified to meet the requirements of the indicating or controlling units. The signal magnitude can be related in terms of the voltage current. (The analog signal information can be converted in to pulse or frequency information. Since output can be modified, modulated or amplified at will, the output signal can be easily used for recording on any suitable multichannel recording device.)
6. The signal can be conditioned or mixed to obtain any combination with outputs of similar transducers or control signals.
7. The electrical or electronic system can be controlled with a very small power level.
8. The electrical output can be easily used, transmitted and processed for the purpose of measurement.

Electrical transducers can be broadly classified into two major categories, (i) Active, (ii) Passive.

An **active transducer** generates an electrical signal directly in response to the physical parameter and does not require an external power source for its operation. Active transducers are self generating devices, which operate under energy conversion principle and generate an equivalent output signal (for example from pressure to charge or temperature to electrical potential).

Typical example of active transducers are piezo electric sensors (for generation of charge corresponding to pressure) and photo voltaic cells (for generation of voltage in response to illumination).

Passive transducers operate under energy controlling principles, which makes it necessary to use an external electrical source with them. They depend upon the change in an electrical parameter (*R*, *L* and *C*).

Typical example are strain gauges (for resistance change in response to pressure), and thermistors (for resistance change corresponding to temperature variations).

Electrical transducers are used mostly to measure non-electrical quantities. For this purpose a detector or sensing element is used, which converts the physical quantity into a displacement. This displacement actuates an electric transducer, which acts as a secondary transducer and give an output that is electrical in nature. This electrical quantity is measured by the standard method used for electrical measurement. The electrical signals may be current, voltage, or frequency; their production is based on *R*, *L* and *C* effects.

A transducer which converts a non-electrical quantity into an analog electrical signal may be considered as consisting of two parts, the sensing element, and the transduction element.

The sensing or detector element is that part of a transducer which responds to a physical phenomenon or to a change in a physical phenomenon. The response of the sensing element must be closely related to the physical phenomenon.

The transduction element transforms the output of a sensing element to an electrical output. This, in a way, acts as a secondary transducer.

Transducers may be further classified into different categories depending upon the principle employed by their transduction elements to convert physical phenomena into output electrical signals.

The different electrical phenomena employed in the transduction elements of transducers are as follows.

1. Resistive
2. Inductive
3. Capacitive
4. Electro magnetic
5. Piezo-electric
6. Photo-emissive
7. Photo-resistive
8. Potentiometric
9. Thermo-electric
10. Frequency generating

SELECTING A TRANSDUCER

13.3

The transducer or sensor has to be physically compatible with its intended application. The following should be considered while selecting a transducer.

1. ***Operating range*** Chosen to maintain range requirements and good resolution.
2. ***Sensitivity*** Chosen to allow sufficient output.
3. ***Frequency response and resonant frequency*** Flat over the entire desired range.
4. ***Environmental compatibility*** Temperature range, corrosive fluids, pressure, shocks, interaction, size and mounting restrictions.
5. ***Minimum sensitivity*** To expected stimulus, other than the measurand.
6. ***Accuracy*** Repeatability and calibration errors as well as errors expected due to sensitivity to other stimuli.
7. ***Usage and ruggedness*** Ruggedness, both of mechanical and electrical intensities versus size and weight.
8. ***Electrical parameters*** Length and type of cable required, signal to noise ratio when combined with amplifiers, and frequency response limitations.

RESISTIVE TRANSDUCER

13.4

Resistive transducers are those in which the resistance changes due to a change in some physical phenomenon. The change in the value of the resistance with a change in the length of the conductor can be used to measure displacement.

Strain gauges work on the principle that the resistance of a conductor or semiconductor changes when strained. This can be used for the measurement of displacement, force and pressure.

The resistivity of materials changes with changes in temperature. This property can be used for the measurement of temperature.

13.4.1 Potentiometer

A resistive potentiometer (pot) consists of a resistance element provided with a sliding contact, called a wiper. The motion of the sliding contact may be translatory or rotational. Some have a combination of both, with resistive elements in the form of a helix, as shown in Fig. 13.1(c). They are known as helipots.

Translatory resistive elements, as shown in Fig. 13.1(a), are linear (straight) devices. Rotational resistive devices are circular and are used for the measurement of angular displacement, as shown in Fig. 13.1(b).

Helical resistive elements are multi turn rotational devices which can be used for the measurement of either translatory or rotational motion. A potentiometer is a passive transducer since it requires an external power source for its operation.

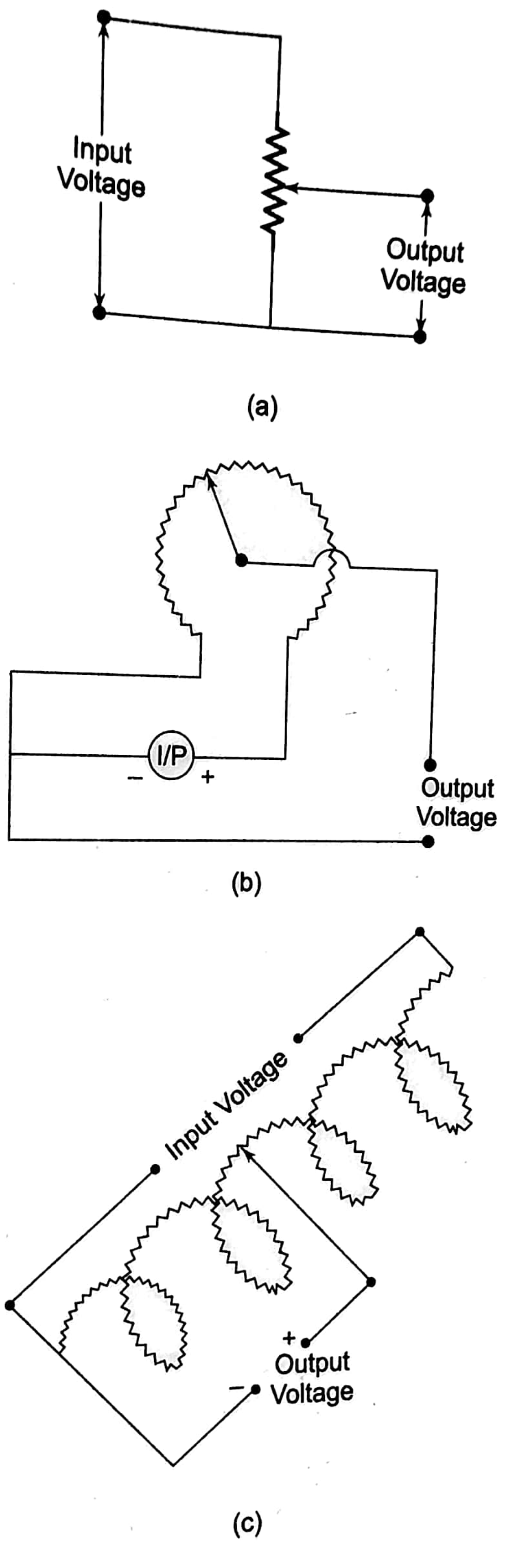

Fig. 13.1 (a) Translatory Type (b) Rotational Type (c) Helipot (Rotational)

Advantage of Potentiometers

1. They are inexpensive.
2. Simple to operate and are very useful for applications where the requirements are not particularly severe.
3. They are useful for the measurement of large amplitudes of displacement.
4. Electrical efficiency is very high, and they provide sufficient output to allow control operations.

Disadvantages

1. When using a linear potentiometer, a large force is required to move the sliding contacts.

2. The sliding contacts can wear out, become misaligned and generate noise.

13.4.2 Resistance Pressure Transducer

Measurement in the resistive type of transducer is based on the fact that a change in pressure results in a resistance change in the sensing elements. Resistance pressure transducers are of two main types. First, the electromechanical resistance transducer, in which a change of pressure, stress, position, displacement or other mechanical variation is applied to a variable resistor. The other resistance transducer is the strain gauge, where the stress acts directly on the resistance. It is very commonly used for stress and displacement measurement in instrumentation.

In the general case of pressure measurement, the sensitive resistance element may take other forms, depending on the mechanical arrangement on which the pressure is caused to act.

Figure 13.1(d) and (e) show two ways by which the pressure acts to influence the sensitive resistance element, i.e. by which pressure varies the resistance element. They are the bellow type, and the diaphragm type. (Yet another is the Bourdon tube of pressure gauge).

In each of these cases, the element moved by the pressure change is made to cause a change in resistance. This resistance change can be made part of a bridge circuit and then taken as either ac or dc output signal to determine the pressure indication.

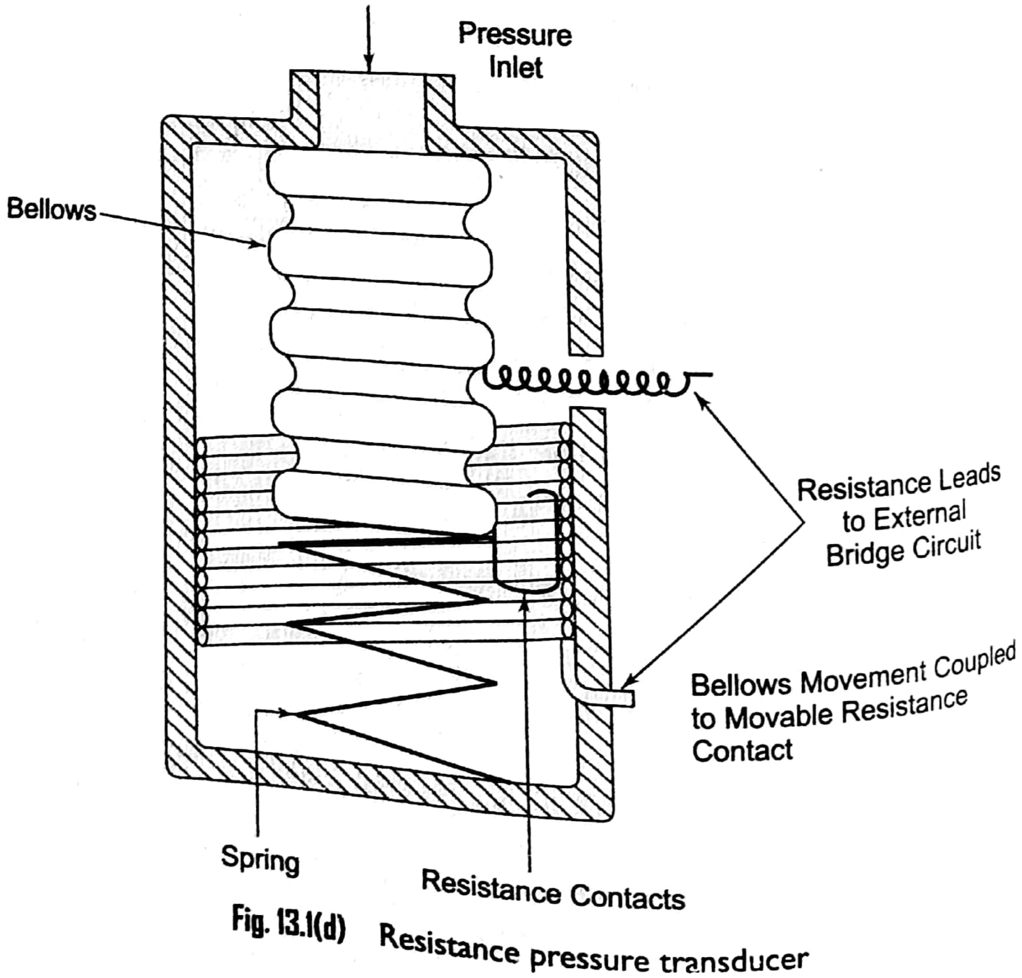
Pressure Inlet
Bellows
Resistance Leads to External Bridge Circuit
Bellows Movement Coupled to Movable Resistance Contact
Spring
Resistance Contacts

Fig. 13.1(d) Resistance pressure transducer

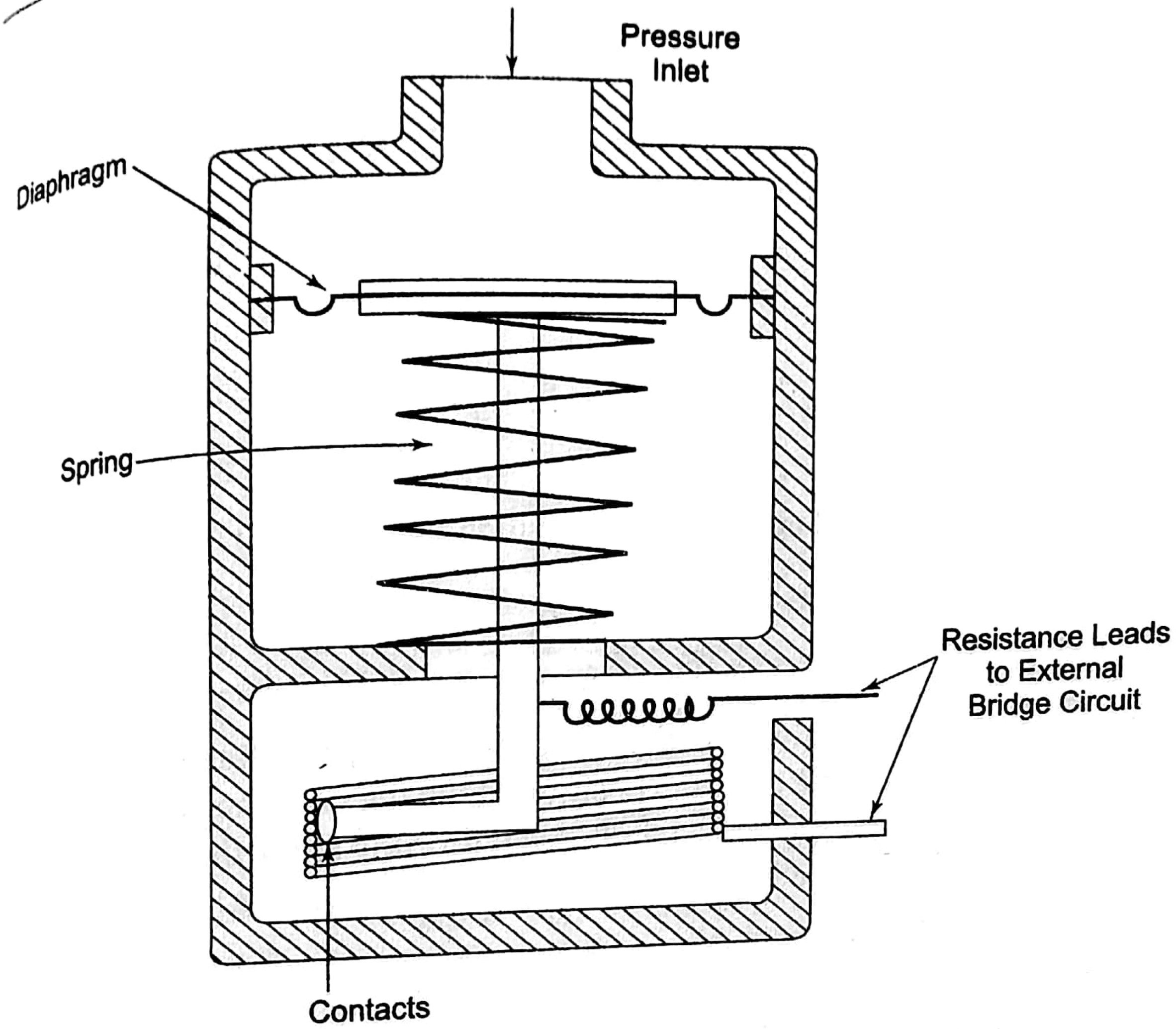

Fig. 13.1(e) Sensitive diaphragm moves the resistance contact

13.5

RESISTIVE POSITION TRANSDUCER

The principle of the resistive transducer is that the physical variable under measurement causes a resistance change in the sensing element. (A common requirement in industrial measurement and control work is to be able to sense the position of an object, or the distance it has moved).

One type of displacement transducer uses a resistive element with a sliding contact or wiper linked to the object being monitored or measured. Thus the resistance between the slider and one end of the resistance element depends on the position of the object. Figure 13.2(a) gives the construction of this type of transducer.

Figure 13.2(b) shows a typical method of use. The output voltage depends on the wiper position and is therefore a function of the shaft position. This voltage may be applied to a voltmeter calibrated in cms for visual display.

(Typical commercial units provide a choice of maximum shaft strokes, from an inch or less to 5 ft or more.) Deviation from linearity of the resistance versus distance specifications can be as low as 0.1 – 1.0%.

Considering Fig. 13.2(b), if the circuit is unloaded, the output voltage V_o is a certain fraction of V_t, depending upon the position of the wiper.

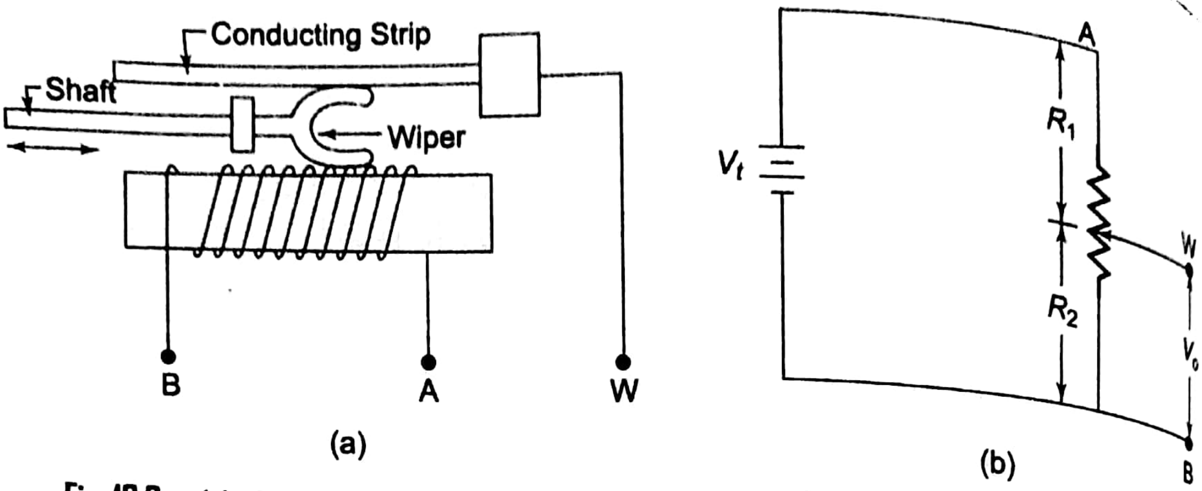

Fig. 13.2 (a) Construction of resistance position transducer (b) Typical method

Therefore,
$$\frac{V_o}{V_t} = \frac{R_2}{R_1 + R_2}$$

When applied to resistive position sensors, this equation shows that output voltage is proportional to R_2, i.e. the position of the wiper of the potentiometer. If the resistance of the transducer is distributed uniformly along the length of travel of the wiper, the resistance is perfectly linear.

Example 13.1 *A displacement transducer with a shaft stroke of 3.0 in. is applied to the circuit of Fig. 13.2(b). The total resistance of the potentiometer is 5 kΩ. The applied voltage V_t is 5 V. When the wiper is 0.9 in. from B, what is the value of the output voltage?*

Solution
$$R_2 = \frac{0.9 \text{ in.}}{3.0 \text{ in.}} \times 5\text{ k} = \frac{9}{30} \times 5\text{ k} = 1500\ \Omega$$

Therefore
$$\frac{V_o}{V_t} = \frac{R_2}{R_1 + R_2};\ V_o = \frac{R_2}{R_1 + R_2} \times V_t$$

$$V_o = \frac{1500}{5\text{ k}} \times 5\ V = \frac{1500}{1\text{ k}} = 1.5\ V$$

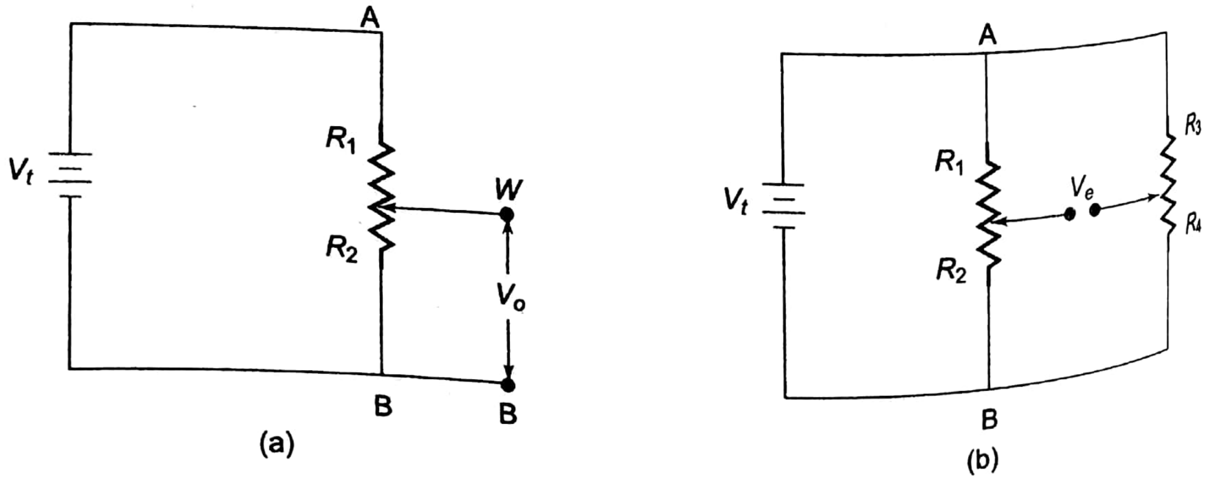

Fig. Ex. 13.1

Example 13.2 *A resistive transducer with a resistance of 5 kΩ and a shaft stroke of 3.0 in. is used in the arrangement in Fig. Ex. 13.1. Potentiometer R_3–R_4 is also 5 k and V_t is 5.0 V. The initial position to be used as a reference point is such that $R_1 = R_2$ (i.e. the shaft is at the centre). At the start of the test, potentiometer R_3–R_4 is adjusted so that the bridge is balanced (V_e = 0). Assuming that the object being monitored moves a maximum resistance of 0.5 in. towards A, what will be the new value of V_c? (Shaft distance is 5 in.)*

Solution If the wiper moves 0.5 in. towards A from the centre, it will have moved 3 in. from *B*.

$$R_2 = \frac{3.0}{5.0} \times 5\text{ k} = 3\text{ k}\Omega$$

$$V_e = VR_2 - VR_4 = \left(\frac{R_2}{R_1 + R_2}\right) \times V_t - \left(\frac{R_4}{R_3 + R_4}\right) \times V_t$$

$$= \left(\frac{3\text{ k}}{5\text{ k}}\right) \times 5\ V - \left(\frac{2.5\text{ k}}{5\text{ k}}\right) \times 5\ V$$

$$= 3\ V - 2.5\ V = 0.5\ V$$

STRAIN GAUGES 13.6

The strain gauge is an example of a passive transducer that uses the variation in electrical resistance in wires to sense the strain produced by a force on the wires.

It is well known that stress (force/unit area) and strain (elongation or compression/unit length) in a member or portion of any object under pressure is directly related to the modulus of elasticity.

Since strain can be measured more easily by using variable resistance transducers, it is a common practice to measure strain instead of stress, to serve as an index of pressure. Such transducers are popularly known as strain gauges.

If a metal conductor is stretched or compressed, its resistance changes on account of the fact that both the length and diameter of the conductor changes. Also, there is a change in the value of the resistivity of the conductor when subjected to strain, a property called the *piezo-resistive effect.* Therefore, resistance strain gauges are also known as *piezo resistive gauges.*

Many detectors and transducers, e.g. load cells, torque meters, pressure gauges. temperature sensors, etc. employ strain gauges as secondary transducers.

When a gauge is subjected to a positive stress, its length increases while its area of cross-section decreases. Since the resistance of a conductor is directly proportional to its length and inversely proportional to its area of cross-section, the resistance of the gauge increases with positive strain. The change in resistance value of a conductor under strain is more than for an increase in resistance due to its dimensional changes. This property is called the piezo-resistive effect.

The following types of strain gauges are the most important.

1. Wire strain gauges
2. Foil strain gauges
3. Semiconductor strain gauges

13.6.1 Resistance Wire Gauge

Resistance wire gauges are used in two basic forms, the unbonded type, and the bonded type.

1. Unbonded Resistance Wire Strain Gauge An unbonded strain gauge consists of a wire streched between two points in an insulating medium, such as air. The diameter of the wire used is about 25 µm. The wires are kept under tension so that there is no sag and no free vibration. Unbonded strain gauges are usually connected in a bridge circuit. The bridge is balanced with no load applied as shown in Fig. 13.3.

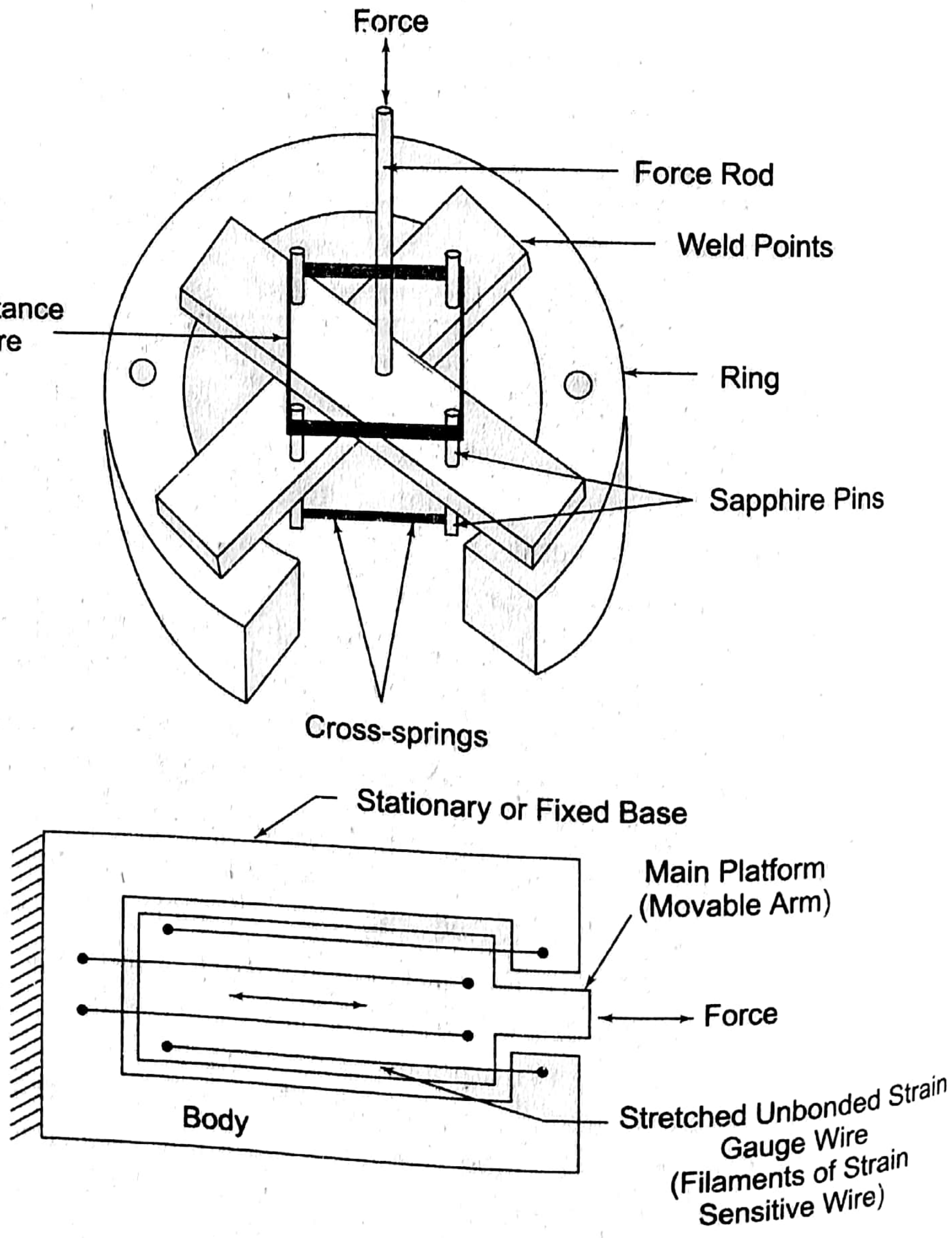

Fig. 13.3 Unbonded strain gauge

When an external load is applied, the resistance of the strain gauge changes, causing an unbalance of the bridge circuit resulting in an output voltage. This voltage is proportional to the strain. A displacement of the order of 50 μm can be detected with these strain gauges.

2. Bonded Resistance Wire Strain Gauges A metallic bonded strain gauge is shown in Fig. 13.4.

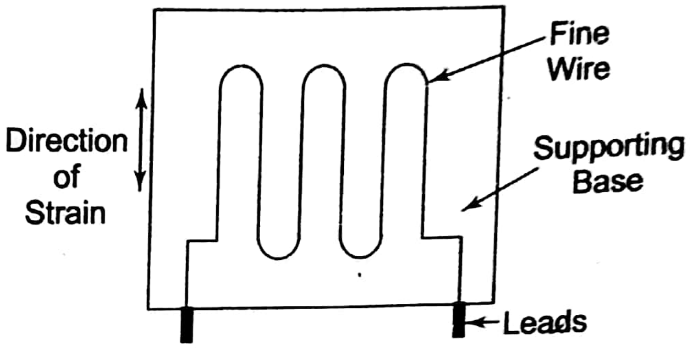

Fig. 13.4 Bonded resistance wire strain gauge

A fine wire element about 25 μm (0.025 in.) or less in diameter is looped back and forth on a carrier (base) or mounting plate, which is usually cemented to the member undergoing stress. The grid of fine wire is cemented on a carrier which may be a thin sheet of paper, bakelite, or teflon. The wire is covered on the top with a thin material, so that it is not damaged mechanically. The spreading of the wire permits uniform distribution of stress. The carrier is then bonded or cemented to the member being studied. This permits a good transfer of strain from carrier to wire.

A tensile stress tends to elongate the wire and thereby increase its length and decrease its cross-sectional area. The combined effect is an increase in resistance, as seen from the following equation

$$R = \frac{\rho \times l}{A}$$

where ρ = the specific resistance of the material in Ωm
l = the length of the conductor in m
A = the area of the conductor in m^2

As a result of strain, two physical parameters are of particular interest.

1. The change in gauge resistance.
2. The change in length.

The measurement of the sensitivity of a material to strain is called the gauge factor (GF). It is the ratio of the change in resistance $\Delta R/R$ to the change in the length $\Delta l/l$

i.e.

$$\text{GF}\,(K) = \frac{\Delta R/R}{\Delta l/l} \tag{13.1}$$

where K = gauge factor
ΔR = the change in the initial resistance in Ω's
R = the initial resistance in Ω (without strain)
Δl = the change in the length in m
l = the initial length in m (without strain)

Since strain is defined as the change in length divided by the original length,

i.e.
$$\sigma = \frac{\Delta l}{l}$$

Eq. (13.1) can be written as

$$K = \frac{\Delta R / R}{\sigma} \tag{13.2}$$

where σ is the strain in the lateral direction.

The resistance of a conductor of uniform cross-section is

$$R = \rho \frac{\text{length}}{\text{area}}$$

$$R = \rho \frac{l}{\pi r^2}$$

Since
$$r = \frac{d}{2} \quad \therefore \quad r^2 = \frac{d^2}{4}$$

$$\therefore \quad R = \rho \frac{l}{\pi\, d^2/4} = \rho \frac{l}{\pi/4\, d^2} \tag{13.3}$$

where ρ = specific resistance of the conductor
l = length of conductor
d = diameter of conductor

When the conductor is stressed, due to the strain, the length of the conductor increases by Δl and the simultaneously decreases by Δd in its diameter. Hence the resistance of the conductor can now be written as

$$R_s = \rho \frac{(l + \Delta l)}{\pi/4 (d - \Delta d)^2} = \frac{\rho (l + \Delta l)}{\pi/4\, (d^2 - 2d\, \Delta d + \Delta d^2)}$$

Since Δd is small, Δd^2 can be neglected

$$\therefore \quad R_s = \frac{\rho\, (l + \Delta l)}{\pi/4\, (d^2 - 2d\, \Delta d)}$$

$$= \frac{\rho\, (l + \Delta l)}{\pi/4 d^2 \left(1 - \frac{2\Delta d}{d}\right)} = \frac{\rho l\, (1 + \Delta l / l)}{\pi/4 d^2 \left(1 - \frac{2\Delta d}{d}\right)} \tag{13.4}$$

Now, Poisson's ratio μ is defined as the ratio of strain in the lateral direction to strain in the axial direction, that is,

$$\mu = \frac{\Delta d / d}{\Delta l / l} \tag{13.5}$$

$$\therefore \quad \frac{\Delta d}{d} = \mu \frac{\Delta l}{l} \tag{13.6}$$

Substituting for $\Delta d/d$ from Eq. (13.6) in Eq. (13.4), we have

$$R_s = \frac{\rho l\,(1+\Delta l/l)}{(\pi/4)\,d^2\,(1-2\mu\,\Delta l/l)}$$

Rationalising, we get

$$R_s = \frac{\rho l\,(1+\Delta l/l)}{(\pi/4)\,d^2\,(1-2\mu\,\Delta l/l)}\,\frac{(1+2\mu\,\Delta l/l)}{(1+2\mu\,\Delta l/l)}$$

$$\therefore \quad R_s = \frac{\rho l}{(\pi/4)\,d^2}\left[\frac{(1+\Delta l/l)}{(1-2\mu\,\Delta l/l)}\,\frac{(1+2\mu\,\Delta l/l)}{(1+2\mu\,\Delta l/l)}\right]$$

$$\therefore \quad R_s = \frac{\rho l}{(\pi/4)\,d^2}\left[\frac{1+2\mu\,\Delta l/l+2\,\Delta l/l+2\mu\;\Delta l/e\;\Delta l/l}{1-4\mu^2\,(\Delta l/l)^2}\right]$$

$$\therefore \quad R_s = \frac{\rho l}{(\pi/4)\,d^2}\left[\frac{1+2\mu\,\Delta l/l+\Delta l/l+2\mu\,\Delta l^2/l^2}{1-4\mu^2\,\Delta l^2/l^2}\right]$$

Since Δl is small, we can neglect higher powers of Δl.

$$\therefore \quad R_s = \frac{\rho l}{(\pi/4)\,d^2}\,[1+2\,\mu\,\Delta l/l+\Delta l/l]$$

$$R_s = \frac{\rho l}{(\pi/4)\,d^2}\,[1+(2\,\mu+1)\,\Delta l/l]$$

$$R_s = \frac{\rho l}{(\pi/4)\,d^2}\,[1+(1+2\,\mu)\,\Delta l/l]$$

$$\therefore \quad R_s = \frac{\rho l}{(\pi/4)\,d^2}+\frac{\rho l}{(\pi/4)\,d^2}\,(\Delta l/l)\,(1+2\,\mu)$$

Since from Eq. (13.3), $R = \dfrac{\rho l}{(\pi/4)\,d^2}$

$$\therefore \quad R_s = R+\Delta R \tag{13.7}$$

where $\Delta R = \dfrac{\rho l}{(\pi/4)\,d^2}\,(\Delta l/l)\,(1+2\,\mu)$

∴ The gauge factor will now be

$$K = \frac{\Delta R/R}{\Delta l/l} = \frac{(\Delta l/l)\,(1+2\mu)}{\Delta l/l}$$

$$= 1+2\,\mu$$

$$\therefore \quad K = 1+2\,\mu \tag{13.8}$$

Example 13.3 *A resistance strain gauge with a gauge factor of 2 is cemented to a steel member, which is subjected to a strain of 1×10^{-6}. If the original resistance value of the gauge is 130 Ω, calculate the change in resistance.*

Solution Given:

$$K = \frac{\Delta R/R}{\Delta l/l}$$

Therefore,

$$\Delta R = K\,R\,\Delta l/l$$

$$\Delta R = 2 \times 130 \times 1 \times 10^{-6} = 260\ \mu\Omega$$

The initial resistance value R of a strain gauge is typically around 120 Ω and the gauge factor may be from (for Nickel) – 12 to + 6. A gauge factor of 2 is reasonable for most strain gauges. Semiconductor gauge have higher sensitivities.

The strain gauge is normally used in a bridge arrangement in which the gauge forms one arm of the bridge. The bridge may be ac or dc actuated. A simple dc arrangement is shown in Fig. 13.5. Only one of the gauges is an active element, producing an output proportional to the strain. The other (dummy) gauge is not strained, but simply balances the bridge (compensation). Since the resistance of the fine wire element is sensitive to temperature as well as stress variation, any change in temperature will cause a change in the bridge balance conditions. This effect can cause error in the strain measurement (thereby affecting the accuracy). Hence, when temperature variations are significant, or when unusual accuracy is required, some compensation must be used. The dummy gauge accomplishes this, because it is placed in the same temperature environment as the active gauges, but not subjected to strain. Consequently, the temperature causes the same change of resistance in the two strain gauges and the bridge balance is not affected by the temperature.

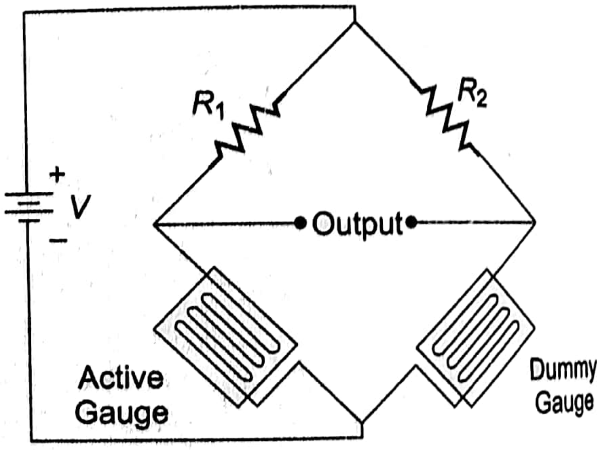

Fig. 13.5 Strain gauge used in bridge arrangement

If the two resistors R_1 and R_2 have negligible temperature coefficients, the bridge retains its balance under conditions of no-strain, at any temperature within its operating range.

(However, one of the two gauges in mounted so that its sensitivity direction is at right angles to the direction of strain.)

The resistance of this dummy gauge is not affected by the deformation of the material and it therefore acts like a passive resistance, with regard to strain measurement.

Since only one gauge responds to the strain, the strain causes bridge unbalance just as in the case of a single gauge.

13.6.2 Types of Strain Gauges (Wire)

1. Grid type
2. Rossette type
3. Torque type
4. Helical type

The *grid arrangement* of the wire element in a bonded strain gauge creates a problem not encountered in the use of unbonded strain gauges. To be useful as a strain gauge, the wire element must measure strain along one axis. Therefore complete and accurate analysis of strain in a rigid member is impossible, unless the direction and magnitude of stress are known. The measuring axis of a strain gauge is its longitudinal axis, which is parallel to the wire element, as shown in Fig. 13.6.

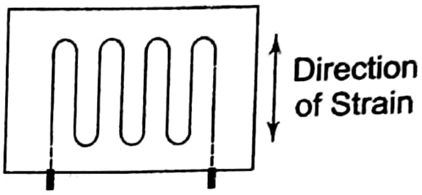

Fig. 13.6 Grid type strain gauge

When a strain occurs in the member being measured, along the transverse axis of the gauge, it also affects the strain being measured parallel to the longitudinal axis. This introduces an error in the response of the gauge.

In most applications, some degree of strain is present along the transverse axis and the transverse sensitivity must be considered in the final gauge output. Transverse sensitivity cannot be completely eliminated, and in highly accurate measurements the resultant gauge error must be compensated for.

If the axis of the strain in a component is unknown, strain gauges may be used to determine the exact direction. The standard procedure is to place several gauges at a point on the member's surface, with known angles between them. The magnitude of strain in each individual gauge is measured, and used in the geometrical determination of the strain in the member. Figure 13.7 shows a three-element strain gauge, called a *Rossette gauge*, in which the angle between any two longitudinal gauge axes is 45°.

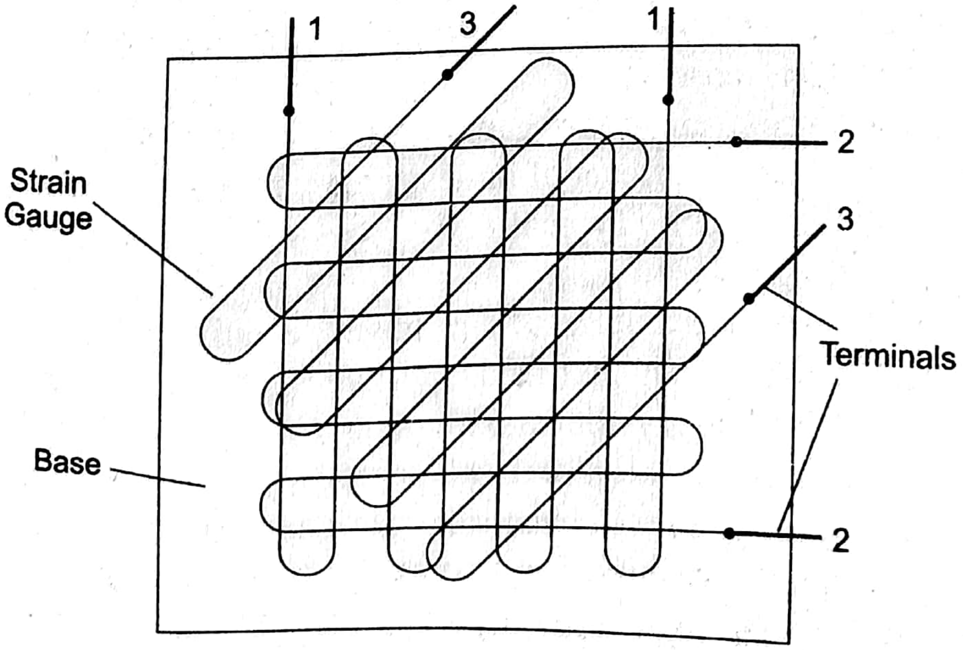

Fig. 13.7 Rossette gauge

The 45° Rossette gauge is, in general, the most popular one. There are different shapes and sizes of strain gauges for various purposes.

Serving a similar, but not specialised, purpose are gauges with specially modified grid configurations, such as those shown in Figs. 13.8(a), (b) and (c).

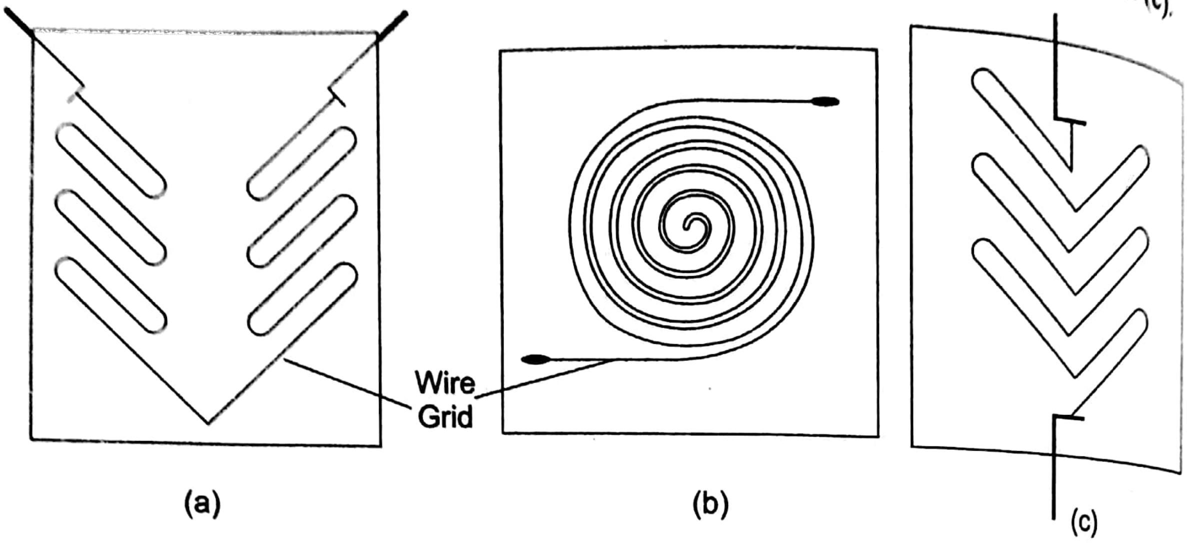

Fig. 13.8 (a) and (c) Torque type gauge (b) Helical gauge

A measurement of this type would be useful at the cross-point of an X-shaped frame.

The latest in strain gauges is the etched foil strain gauge. This device uses the technique of PCB design. Its physical and electrical characteristics are superior to bonded wire strain gauges in almost every respect.

The size of strain gauges varies with application. They can be as small as 3 sq.mm. Usually they are larger, but not more than 2.5 mm long and 12.5 mm wide.

To obtain good results, it is desirable that a resistance wire strain gauge have the following characteristics.

1. The strain gauge should have a high value of gauge factor (a high value of gauge factor indicates a large change in resistance for particular strain, implying high sensitivity).
2. The resistance of the strain gauge should be as high as possible, since this minimises the effects of undesirable variations of resistance in the measurement circuit. Typical resistances of strain gauges are 120 Ω, 350 Ω and 1000 Ω.

   A high resistance value results in lower sensitivity. Hence, in order to get high sensitivity, higher bridge voltages have to be used. The bridge voltage is limited by the maximum current carrying capacity of the wires, which is typically 30 mA.
3. The strain gauge should have a low resistance temperature coefficient. This is necessary to minimise errors on account of temperature variation, which affects the accuracy of measurements. (Temperature compensation is also used.).
4. The strain gauge should not have hysteresis effects in its response.

5. In order to maintain constancy of calibration over the entire range of the strain gauge, it should have linear characteristics, i.e. the variation in resistance should be a linear function of the strain.
6. Strain gauges are frequently used for dynamic measurements and hence their frequency response should be good. Linearity should be maintained within specified accuracy limits over the entire frequency range.
7. Leads used must be of materials which have low and stable resistivity and low resistance temperature coefficient.

13.6.3 Foil Strain Gauge

This class of strain gauges is an extension of the resistance wire strain gauge. The strain is sensed with the help of a metal foil. The metals and alloys used for the foil and wire are nichrome, constantan (Ni + Cu), isoelastic (Ni + Cr + Mo), nickel and platinum.

Foil gauges have a much greater dissipation capacity than wire wound gauges, on account of their larger surface area for the same volume. For this reason, they can be used for a higher operating temperature range. Also, the large surface area of foil gauges leads to better bonding.

Foil type strain gauges have similar characteristics to wire strain gauges. Their gauge factors are typically the same.

The advantage of foil type strain gauges is that they can be fabricated on a large scale, and in any shape. The foil can also be etched on a carrier.

Etched foil gauge construction consists of first bonding a layer of strain sensitive material to a thin sheet of paper or bakelite. The portion of the metal to be used as the wire element is covered with appropriate masking material, and an etching solution is applied to the unit. The solution removes that portion of the metal which is not masked, leaving the desired grid structure intact.

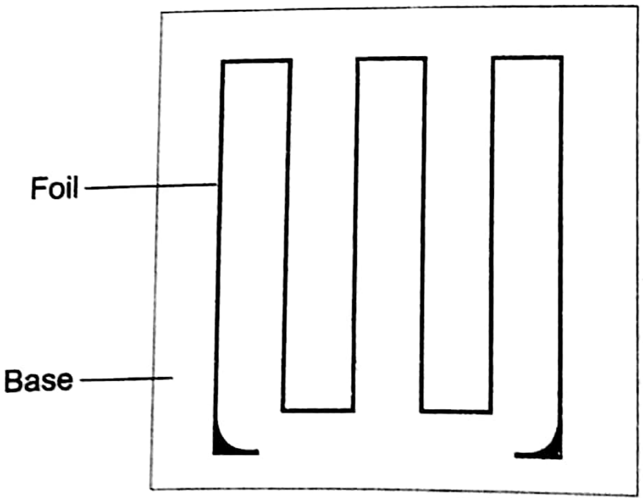

Fig. 13.9 Foil type strain gauge

This method of construction enables etched foil strain gauges to be made thinner than comparable wire units, as shown in Fig. 13.9. This characteristics, together with a greater degree of flexibility, allows the etched foil to be mounted in more remote and restricted places and on a wide range of curved surfaces.

The longitudinal sensitivity of the foil gauge is approximately 5% greater than that of similar wire elements. The transverse strain sensitivity of this gauge is smaller 1/3 to 1/2 of similar wire gauges. The hysteresis of the foil gauge is also 1/3 to 1/2 of a wire strain gauge.

(The term hysteresis, as used in strain gauges, is defined as follows. If the resistance of a strain gauge is measured with no strain applied, and the then stressed to its maximum usable resistance value, the measured resistan after the stress is removed, differs from the original value. The inability of gauge element to resume the exact physical form it had before being elongat produces the difference in resistance. This effect is called *hysteresis*.)

The resistance film formed is typically 0.2 mm thick. The resistance value commercially available foil gauges is between 50 and 1000 Ω. The resistan films are vacuum coated with ceramic film and deposited on a plastic backi for insulation.

13.6.4 Semiconductor Strain Gauge

To have a high sensitivity, a high value of gauge factor is desirable. A high gaug factor means relatively higher change in resistance, which can be easily measure with a good degree of accuracy.

Semiconductor strain gauges are used when a very high gauge factor i required. They have a gauge factor 50 times as high as wire strain gauges. Th resistance of the semiconductor changes with change in applied strain.

Semiconductor strain gauges depend for their action upon the piezo resistiv effect, i.e. change in value of the resistance due to change in resistivity, unlik metallic gauges where change in resistance is mainly due to the change i dimension when strained. Semiconductor materials such as germanium an silicon are used as resistive materials.

A typical strain gauge consists of a strain material and leads that are placed in a protective box, as shown in Fig. 13.10. Semiconductor wafer or filaments which have a thickness of 0.05 mm are used. They are bonded on suitable insulating substrates, such as teflon.

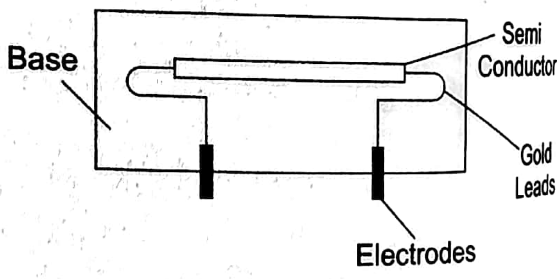

Fig. 13.10 Semiconductor strain gauge

Gold leads are generally used for making contacts. These strain gauges can be fabricated along with an IC Op Amp which can act as a pressure sensitive transducer. The large gauge factor is accompanied by a thermal rate of change of resistance approximately 50 times higher than that for resistive gauges. Hence, a semiconductor strain gauge is as stable as the metallic type, but has a much higher output.

Simple temperature compensation methods can be applied to semiconductor strain gauges, so that small values of strain, that is micro strains, can also be measured.

The gauge factor of this type of semiconductor strain gauge is 130 ± 10% for a unit of 350 Ω, 1" long, 1/2" wide and 0.005" thick. The gauge factor is determined at room temperature at a tensile strain level of 1000 micro strain (1000 micro in/in. of length). The maximum operating tensile strain is ± 3000 micro strain, with a power dissipation of 0.1 W. The semiconductor strain gauge also has low hysteresis and is [illegible] methods of temperature compensation. The semiconductor strain gauge has proved itself to be a stable and practical device for operation with conventional indicating and recording systems, to measure small strains from 0.1–500 micro strain.

Advantages of Semiconductor Strain Gauge

1. Semiconductor strain gauges have a high gauge factor of about + 130. This allows measurement of very small strains, of the order of 0.01 micro strain.
2. Hysteresis characteristics of semiconductor strain gauges are excellent, i.e. less than 0.05%.
3. Life in excess of 10×10^6 operations and a frequency response of 10^{12} Hz.
4. Semiconductor strain gauges can be very small in size, ranging in length from 0.7 to 7.0 mm.

Disadvantages

1. They are very sensitive to changes in temperature.
2. Linearity of semiconductor strain gauges is poor.
3. They are more expensive.

13.7

RESISTANCE THERMOMETER*

The resistance of a conductor changes when its temperature is changed. This property is utilised for the measurement of temperature. The resistance thermometer is an instrument used to measure electrical resistance in terms of temperature, i.e. it uses the change in the electrical resistance of the conductor to determine the temperature.

The main part of a resistance thermometer is its sensing element. The characteristics of the sensing element determines the sensitivity and operating temperature range of the instrument.

(There are three common types of temperature sensitive resistive elements in use, the wire wound resistance, the thermistor and the PTC semiconductor resistance.)

The sensing element may be any material that exhibits a relatively large resistance change with change in temperature. Also, the material used should be stable in its characteristics, i.e. neither its resistance nor its temperature coefficient of resistance should undergo permanent change with use or age.

To maintain the calibration of a resistance thermometer, it is necessary to consider its stability. The need for stability frequently limits the temperature range over which the sensing element may be used.

Another desirable characteristic for a sensing element is a linear change in resistance with change in temperature.

The speed with which a resistive element responds to changes in temperature is important when the measured temperature is subjected to rapid variations. The smaller a given sensing element, the less heat required to raise its temperature, and the faster its response.

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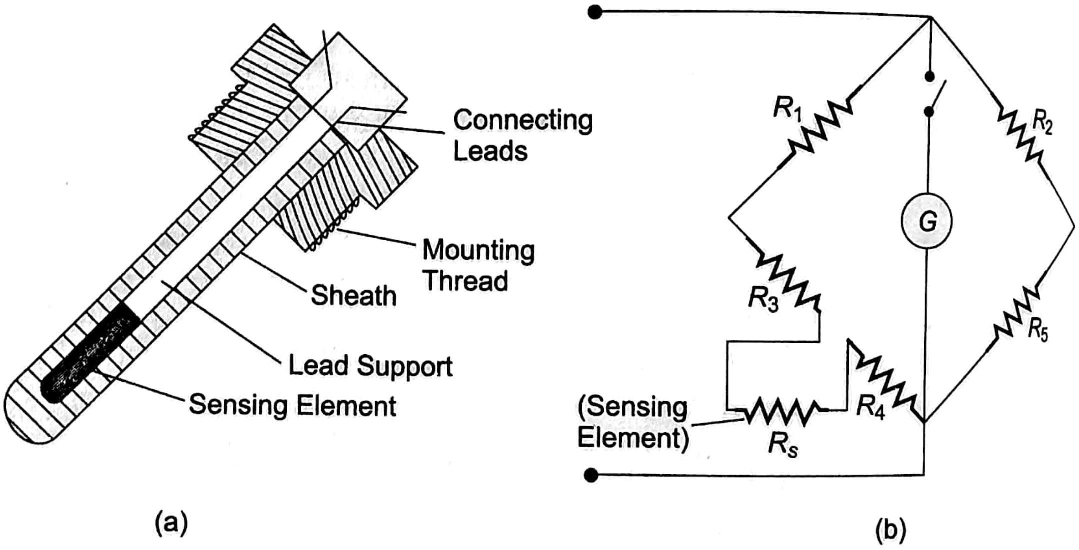
*Also refer Sec. 13.20.2 (RTD's

Platinum, nickel and copper are the metals most commonly used to measure temperature. The resistivity of platinum tends to increase less rapidly at higher temperatures than for other metals, hence it is a commonly used material for resistance thermometers. The temperature range over which platinum has stability is – 260–1100°C.

Figure 13.11(a) shows an industrial platinum resistance thermometer.

The changes in resistance caused by changes in temperature are detected by a Wheatstone bridge, as shown in Fig. 13.11(b). Hence, the temperature sensing element, which may be nickel, copper or platinum contained in a bulb or well, along with the balancing bridge, form the essential components of a temperature measuring system based upon this principle.



(a) (b)

Fig. 13.11 (a) Industrial platinum resistance thermometer (b) Bridge circuit

The sensing element R_s is made of a material having a high temperature coefficient, and R_1, R_2, and R_5 are made of resistances that are practically constant under normal temperature changes.

When no current flows through the galvanometer, the normal principle of Wheatstone's bridge states the ratio of resistance is

$$\frac{R_1}{R_2} = \frac{R_s}{R_5}$$

In normal practice, the sensing element is away from the indicator, and its leads have a resistance, say R_3, R_4.

Therefore,

$$\frac{R_1}{R_2} = \frac{R_3 + R_s + R_4}{R_5}$$

Now it resistance R_s changes, balance cannot be maintained and the galvanometer shows a deflection, which can be calibrated to give a suitable temperature scale.

Advantages of R
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Advantages of Resistance Thermometers The measurement of temperature by the electrical resistance method has the following advantages and characteristics.

1. The measurement is very accurate.
2. It has a lot of flexibility with regard to choice of measuring equipment.
3. Indicators, recorders or controllers can also be operated.
4. More than one resistance element can be clubbed to the same indicating/ recording instrument.
5. The temperature sensitive resistance element can be easily installed and replaced.
6. The accuracy of the measuring circuit can be easily checked by substituting a standard resistor for the resistive element.
7. Resistive elements can be used to measure differential temperature.
8. Resistance thermometers have a wide working range without loss of accuracy, and can be used for temperature ranges (–200°C to + 650°C).
9. They are best suited for remote indication.
10. The resistive element response time is of the order of 2 to 10s
11. The limits of error of a resistive element are ± 0.25% of the scale reading.
12. The size of the resistive element may be about 6 – 12 mm in diameter and 12 – 75 mm in length.
13. Extremely accurate temperature sensing.
14. No necessity of temperature compensation.
15. Stability of performance over long periods of time.

Limitations of Resistance Thermometer

1. High cost
2. Need for bridge circuit and power source
3. Possibility of self-heating
4. Large bulb size, compared to a thermocouple

THERMISTOR

13.8

The electrical resistance of most materials changes with temperature. By selecting materials that are very temperature sensitive, devices that are useful in temperature control circuits and for temperature measurements can be made.

Thermistor (THERMally sensitive resISTOR) are non-metallic resistors (semiconductor material), made by sintering mixtures of metallic oxides such as manganese, nickel, cobalt, copper and uranium.

Thermistors have a Negative Temperature Coefficient (NTC), i.e. resistance decreases as temperature rises. Figure 13.12 shows a graph of resistance vs temperature for a thermistor. The resistance at room temperature (25°C) for typical commercial units ranges from 100 Ω to 10 MΩ. They are suitable for use only up to about 800°C. In some cases, the resistance of thermistors at room temperature may decrease by 5% for each 1°C rise in temperature. This high sensitivity to temperature changes makes the thermistor extremely useful for precision temperature measurements, control and compensation.

The smallest thermistors are made in the form of beads. Some are as small as 0.15 mm (0.006 in.) in diameter. These may come in a glass coating or sealed in the tip of solid glass probes. Glass probes have a diameter of about 2.5 mm and a length which varies from 6 – 50 mm. The probes are used for measuring the temperature of liquids. The resistance ranges from 300 Ω to 100 MΩ.

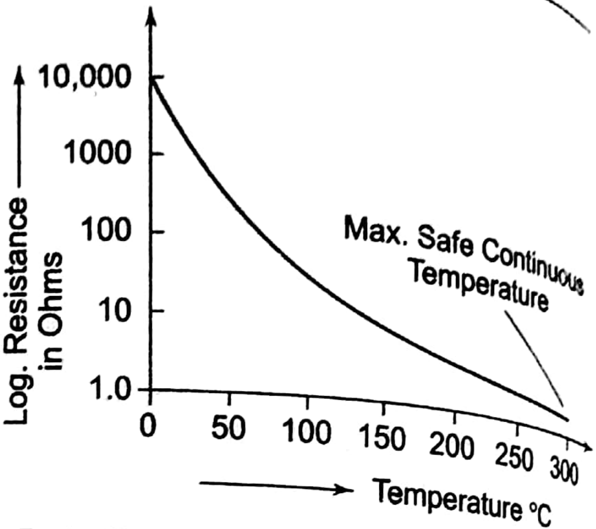


Fig. 13.12 Resistance vs temperature graph of a thermistor

Where greater power dissipations is required, thermistors may be obtained in disc, washer or rod forms.

Disc thermistors about 10 mm in diameter, either self supporting or mounted on a small plate, are mainly used for temperature control. These thermistors are made by pressing themistors material under several tons of pressure in a round die to produce flat pieces 1.25 – 25 mm in diameter and 0.25 – 0.75 mm thick, having resistance values of 1 Ω to 1 MΩ. These are sintered and coated with silver on two flat surfaces.

Washer thermistors are made like disc thermistors, except that a hole is formed in the centre in order to make them suitable for mounting on a bolt. Rod thermistors are extruded through dies to make long cylindrical units of 1.25, 2.75, and 4.25 mm in diameter and 12.5 – 50 mm long. Leads are attached to the end of the rods. Their resistance usually varies from 1 – 50 kΩ.

The advantage of rod thermistors over other configurations is the ability to produce high resistance units with moderately high power handling capability.

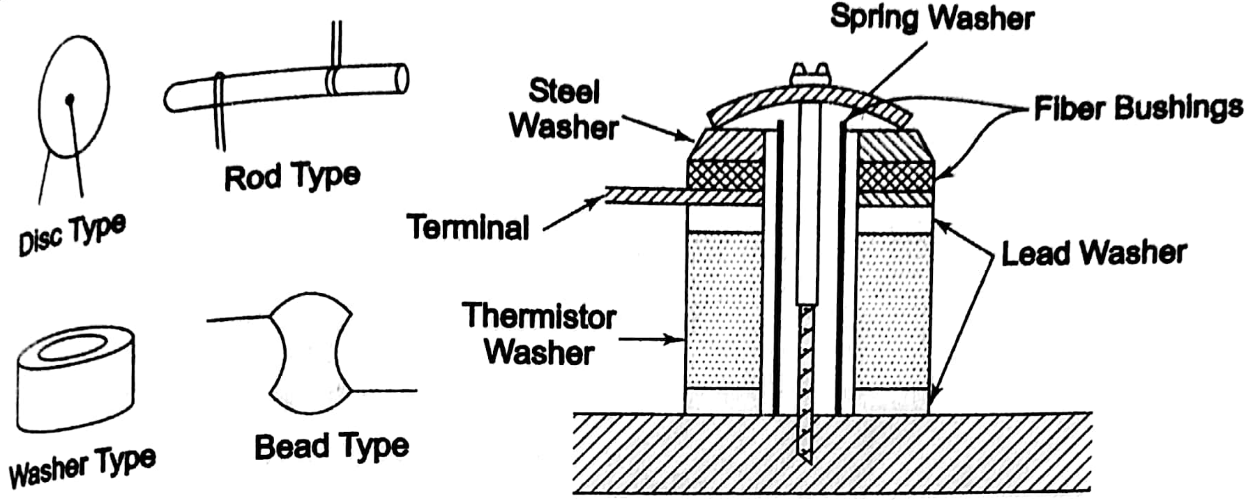
Thermistors can be connected in series/parallel combinations for applications requiring increased power handling capability. High resistance units find application in measurements that employ low lead wires or cables.

Thermistors are chemically stable and can be used in nuclear environments. Their wide range of characteristics also permits them to be used in limiting and regulation circuits, as time delays, for integration of power pulses, and as memory units.

Typical thermistor configurations are as shown in Fig. 13.13(a). Figure 13.13(b) shows a bush type thermistor.

A thermistor in one arm of a Wheatstone bridge provides precise temperature information. Accuracy is limited, in most applications, only by the readout devices.

Thermistors are non-linear devices over a temperature range, although now units with better than 0.2% linearity over the 0–100°C temperature range are available. The typical sensitivity of a thermistor is approximately 3 mV/°C at 200°C.



(a) (b)

Fig. 13.13 (a) Various configurations of thermistor (b) Bush-type thermistor

Advantages of Thermistor

1. Small size and low cost.
2. Fast response over narrow temperature range.
3. Good sensitivity in the NTC region.
4. Cold junction compensation not required due to dependence of resistance on absolute temperature.
5. Contact and lead resistance problems not encountered due to large R_{th} (resistance).

Limitations of Thermistor

1. Non-linearity in resistance vs temperature characteristics.
2. Unsuitable for wide temperature range.
3. Very low excitation current to avoid self-heating.
4. Need of shielded power lines, filters, etc. due to high resistance.

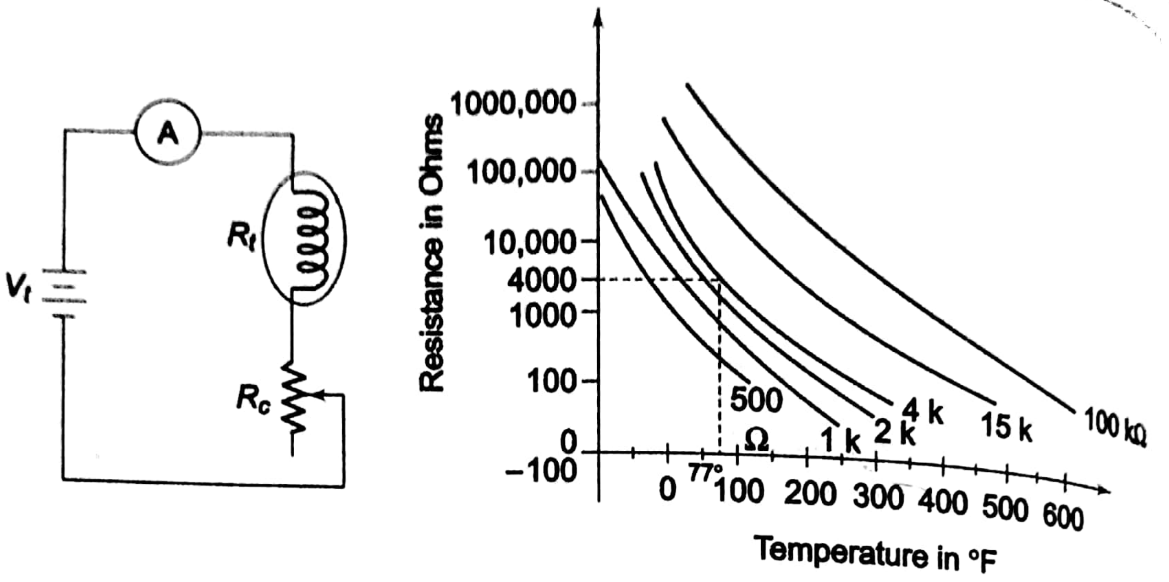
Example 13.4 *The circuit of Fig. Ex. 13.2 (a) is to be used for temperature measurement. The thermistor is a 4 kΩ type. The meter is a 50 mA meter with a resistance of 3 Ω, R_c is set to 17 Ω, and supply V_t is 15 V. What will be the meter reading at 77°F (25°C) and at 150°F.*

Solution From the graph of temperature versus resistance, the resistance at 25°C is 4 kΩ. Therefore the current at 25°C is

$$I = \frac{V_t}{R_t} = \frac{15}{4000 + 17 + 3} = \frac{15}{4020} = 3.73 \text{ mA}.$$

At 150°F, the graph shows that the thermistor resistance is approximately 950 Ω. The meter reading will then be

$$I = \frac{V_t}{R_t} = \frac{15}{950 + 17 + 3} = \frac{15}{970} = 15.5 \text{ mA}.$$



(a)

(b)

Fig. Ex. 13.2

INDUCTIVE TRANSDUCER

13.9

Inductive transducers may be either of the self generating or the passive type. The self generating type utilises the basic electrical generator principle, i.e. a motion between a conductor and magnetic field induces a voltage in the conductor (generator action). This relative motion between the field and the conductor is supplied by changes in the measured.

An inductive electromechanical transducer is a device that converts physical motion (position change) into a change in inductance.

Transducers of the variable inductance type work upon one of the following principles.

1. Variation of self inductance
2. Variation of mutual inductance

Inductive transducers are mainly used for the measurement of displacement. The displacement to be measured is arranged to cause variation in any of three variables

1. Number of turns
2. Geometric configuration
3. Permeability of the magnetic material or magnetic circuits

For example, let us consider the case of a general inductive transducer. The inductive transducer has N turns and a reluctance R. When a current i is passed through it, the flux is

$$\phi = \frac{Ni}{R}$$

Therefore $$\frac{d\phi}{dt} = \frac{N}{2} \times \frac{di}{dt} - \frac{Ni}{R^2} \times \frac{dR}{dt}$$

If the current varies very rapidl

$$\frac{d\phi}{dt} = \frac{N}{2} \times \frac{di}{dt}$$

But emf induced in the coil is given by $e = N \times d\phi/dt$

Therefore $$e = N \times \frac{N}{2} \times \frac{di}{dt} = \frac{N^2}{R} \times \frac{di}{dt} \tag{13.9}$$

Also the self inductance is given by

$$L = \frac{e}{di/dt} = \frac{N^2}{R} \tag{13.10}$$

Therefore, the output from an inductive transducer can be in the form of either a change in voltage or a change in inductance.

13.9.1 Change in Self Inductance with Numbers of Turns

The output may be caused by a change in the number of turns.

Figures 13.14(a) and (b) are transducers used for the measurement of displacement of linear and angular movement respectively.

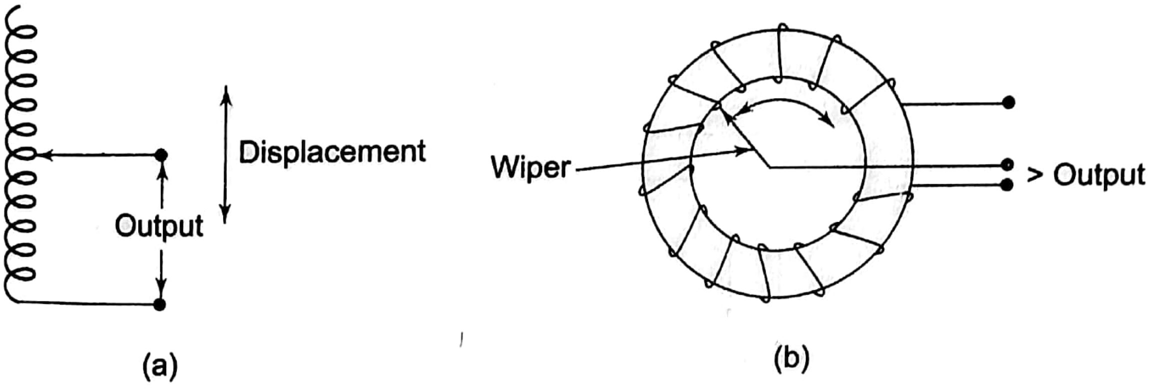


Fig. 13.14 (a) Linear inductive transducer (using air core)
(b) Angular inductive transducer (using ferrite core)

Figure 13.14(a) is an air cored transducer for measurement of linear displacement.

Figure 13.14(b) is an iron cored coil used for the measurement of angular displacement.

In both cases, as the number of turns are changed, the self inductance and the output also changes.

13.9.2 Transducer Working on the Principle of Change in Self Inductance with Change in Permeability

Figure 13.15 shows an inductive transducer which works on the principle of the variation of permeability causing a change in self inductance. The iron core is surrounded by a winding. If the iron core is inside the winding, its permeability is increased, and so is the inductance. When the iron core is moved out of the winding, the permeability decreases, resulting in a reduction of the self inductance of the coil. This transducer can be used for measuring displacement.

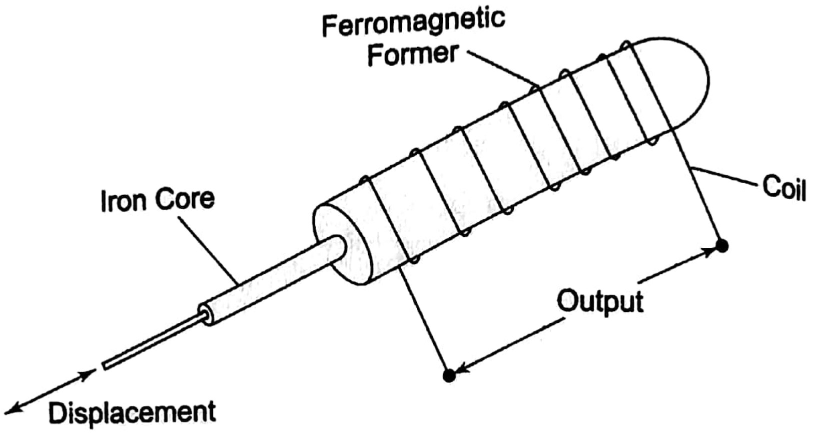


Fig. 13.15 Inductive transducer working on the principle of variation of permeability

13.9.3 Variable Reluctance Type Transducer

A transducer of the variable type consists of a coil wound on a ferromagnetic core. The displacement which is to be measured is applied to a ferromagnetic target. The target does not have any physical contact with the core on which it is mounted. The core and the target are separated by an air gap, as shown in Fig. 13.16(a).

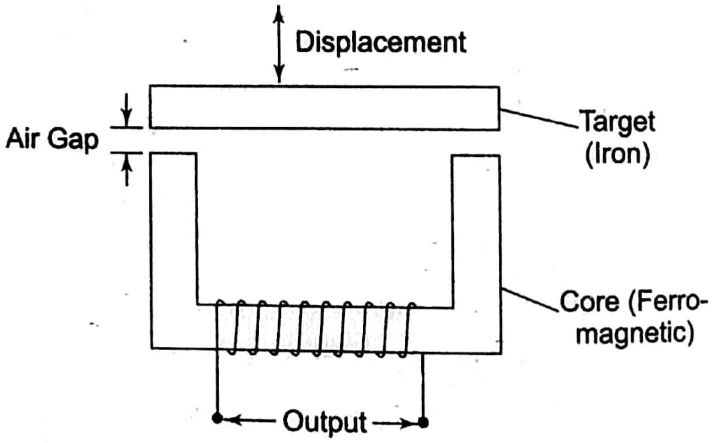


Fig. 13.16 (a) Variable reluctance transducer

The reluctance of the magnetic path is determined by the size of the air gap. The inductance of the coil depends upon the reluctance of the magnetic circuits.

The self inductance of the coil is given by

$$L = \frac{N^2}{R_i + R_g} \tag{13.11}$$

where N = number of turns
R_i = reluctance of iron parts
R_g = reluctance of air gap

The reluctance of the iron part is negligible compared to that of the air gap.

Therefore $$L = N^2/R_g \tag{13.12}$$

But reluctance of the air gap is given by

$$R_g = \frac{l_g}{\mu_o \times A_g} \tag{13.13}$$

where l_g = length of the air gap

A_g = area of the flux path through air

μ_o = permeability

R_g is proportional to l_g, as μ_o and A_g are constants.

Hence L is proportional to $1/lg$, i.e. the self inductance of the coil is inversely proportional to the length of the air gap.

When the target is near the core, the length is small and therefore the self inductance large. But when the target is away from the core the reluctance is large, resulting in a smaller self inductance value. Hence the inductance of the coil is a function of the distance of the target from the core, i.e. the length of the air gap.

Since it is the displacement which changes the length of the air gap, the self inductance is a function of displacement, albeit a non-linear one.

A variable reluctance bridge is shown in Fig. 13.16(b).

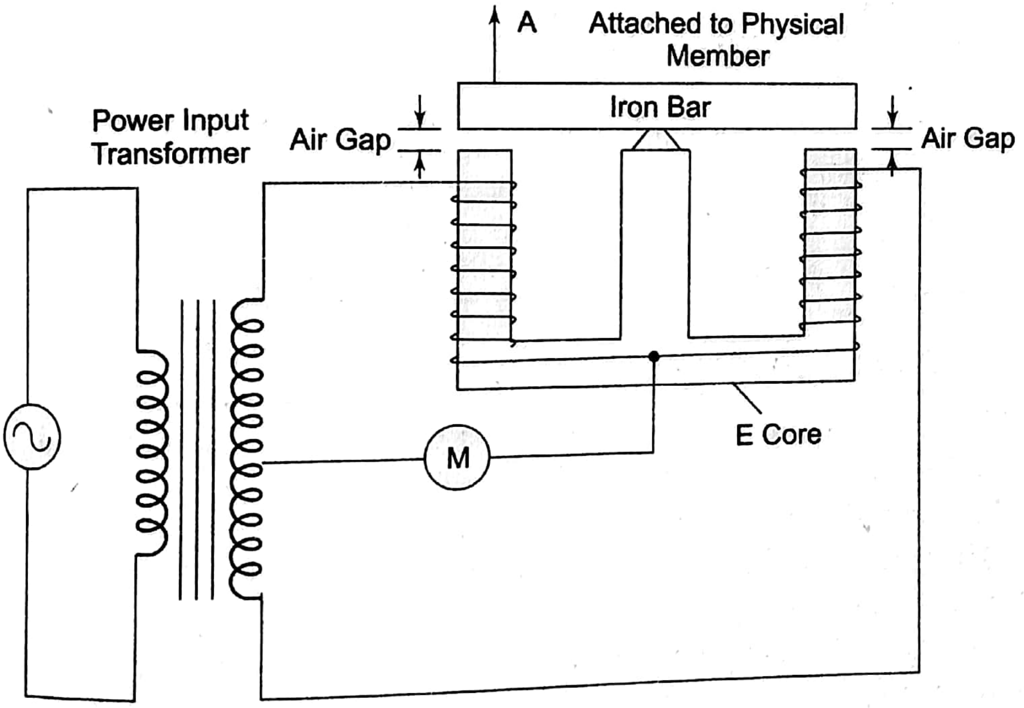


Fig. 13.16 (b) Variable reluctance bridge circuit

A separate coil is wound on each outside leg of an E core and an iron bar is pivoted on the centre leg. A magnet extends from each outside leg through an air gap and through the iron bar to the centre leg.

The moving member is attached to one end of the iron bar and causes the bar to wobble back and forth, thereby varying the size of each air gap.

The bridge consists of two transducer coils and a tapped secondary of the input power transformers. It is balanced only when the inductance of the two transducer coils are equal, i.e. when the iron bar is in a nearly exact horizontal position and the air gaps are equal.

Whenever the iron bar at point A moves and alters the air gap, the bridge becomes unbalanced by an amount proportional to the change in inductance, which in turn is proportional to the displacement of the moving member.

The increase and decrease of the inductance with varying air gap sizes is non-linear, and so is the output. Also, the flux density within the air gaps is easily affected by external fields.

Example 13.5 *A variable reluctance type inductive transducer has a coil of inductance of 2500 μH When the target made of ferromagnetic material is 1mm away from the core. Calculate the value of inductance when a displacement of 0.04 mm is applied to the target in a direction moving it towards the core.*

Solution Given inductance with gap length of 1 mm is $L = 2500\ \mu\text{H}$

Step 1: Length of air gap when a displacement is applied to the target

$$= 1.00 - 0.04 = 0.96\ \text{mm}$$

Step 2: Now inductance is inversely proportional to the length of air gap

Therefore 'L' with gap length of 0.96 mm

$$= L + \Delta L = 2500\ \mu\text{H} \times \frac{1}{0.96\ \text{mm}} = 2604\ \mu\text{H}$$

Step 3: Therefore, change in inductance

$$\Delta L = 2604\ \mu\text{H} - 2500\ \mu\text{H} = 104\ \mu\text{H}$$

DIFFERENTIAL OUTPUT TRANSDUCERS 13.10

The differential output transducer consists of a coil which is divided into two parts, as shown in Figs. 13.17(a) and (b).

(Inductive transducers using self inductance as a variable use one coil, while those using mutual inductance as a variable use multiple coils.)

Normally the change in self inductance, ΔL, for inductive transducers, (working on the principle of change of self inductance) is not sufficient for detection of subsequent stages of the instrumentation system.

However, if successive stages of the instrument respond to ΔL or ΔM, rather than $L + \Delta L$, or $M + \Delta M$, the sensitivity and accuracy will be much higher.

The transducers can be designed to provide two outputs, one of which represents inductance (self or mutual) and the other the decrease in inductance (self or mutual). The succeeding stages of the instrumentation system measure the difference between these outputs. This is known as differential output.

Advantages of Differential Output

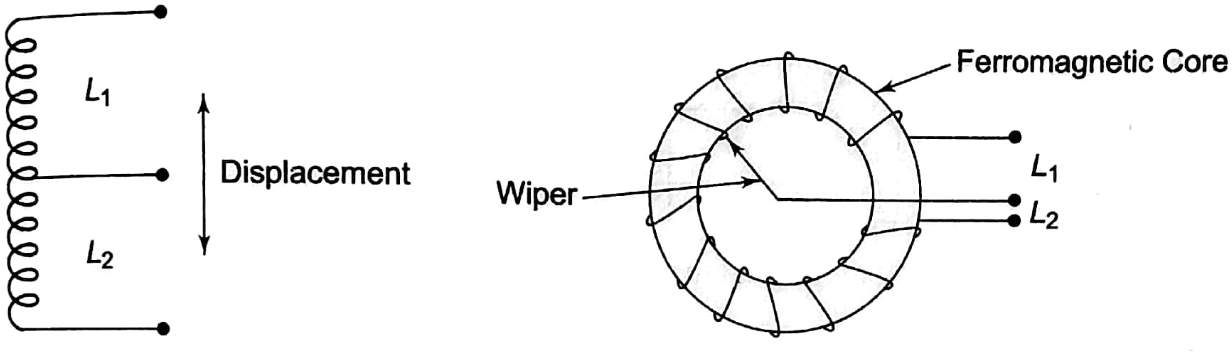
1. Sensitivity and accuracy are increased.
2. Output is less affected by external magnetic fields.
3. Effective variations due to temperature changes are reduced.
4. Effects of change in supply voltages and frequency are reduced.

In response to a physical signal (which is normally displacement), the inductance of one part increases from L to $L + \Delta L$, while that of the other part decreases from L to $L - \Delta L$. The change is measured as the difference of the two, resulting in an output of $2\,\Delta L$ instead of ΔL, when one winding is used. This increases the sensitivity and also eliminates error.

Inductive transducers using the change in the number of turns to cause a change in the self inductance are shown in Fig. 13.17.

Figure 13.17(a) is used for measurement of linear displacement using an air cored coil.

Figure 13.17(b) is used for the measurement of angular displacement using an iron cored coil.



(a) (b)

Fig. 13.17 (a) Linear differential output transducer (b) Angular differential output transducer

Figure 13.18 shows an inductive transducer giving a differential output. The output represents a change of self inductance due to change of reluctance. (This inductive transducer also works on the principle of change of self inductance of the two coils with change in reluctance of the path of the magnetic circuit. The target as well as cores on which the coil is wound are made up of iron.)

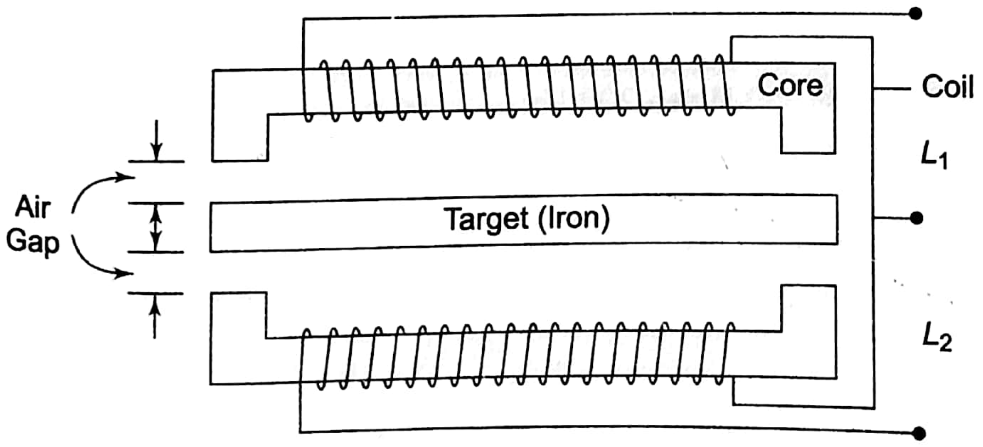


Fig. 13.18 Inductive transducer differential output (Reluctance principle)

LINEAR VARIABLE DIFFERENTIAL TRANSDUCER (LVDT)

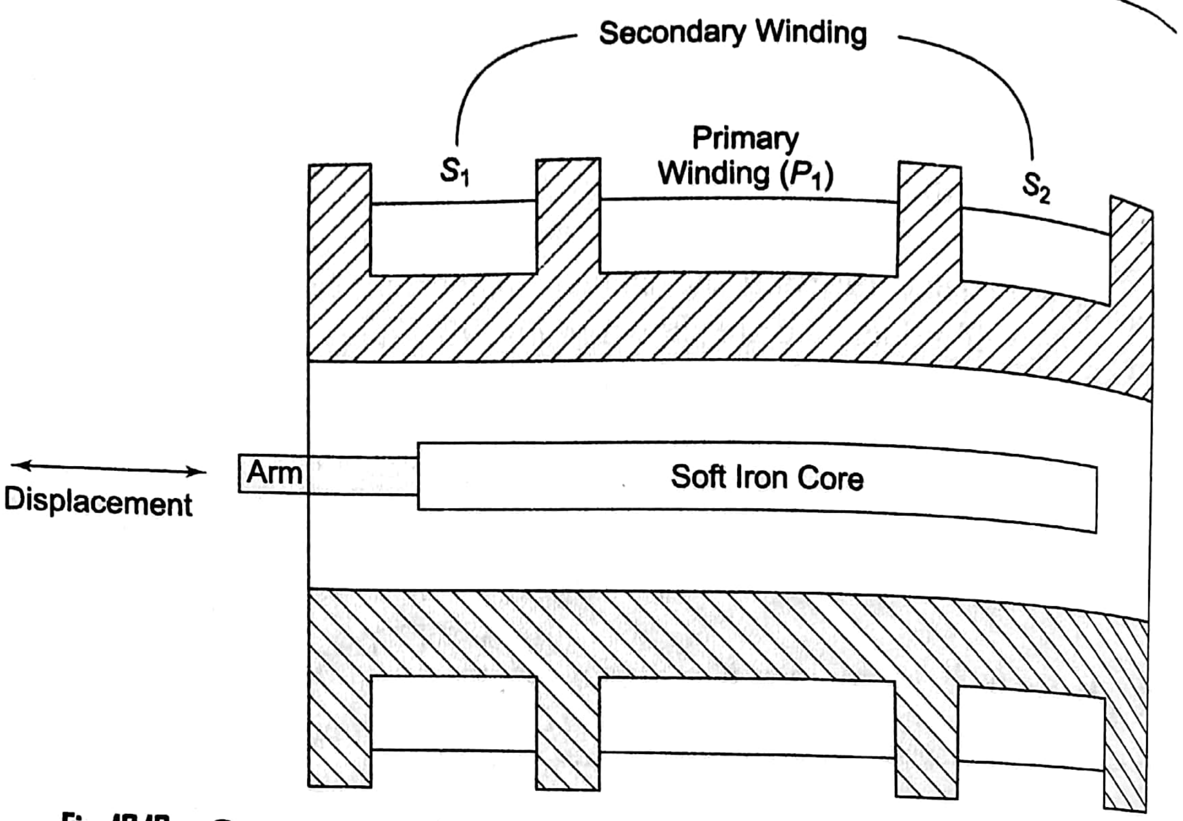


Fig. 13.19 Construction of a linear variable differential transducer (LVDT)

The transformer consists of a single primary winding P_1 and two secondary windings S_1 and S_2 wound on a hollow cylindrical former. The secondary windings have an equal number of turns and are identically placed on either side of the primary windings. The primary winding is connected to an ac source.

An movable soft iron core slides within the hollow former and therefore affects the magnetic coupling between the primary and the two secondaries.

The displacement to be measured is applied to an arm attached to the soft iron core.

(In practice, the core is made up of a nickel-iron alloy which is slotted longitudinally to reduce eddy current losses.)

When the core is in its normal (null) position, equal voltages are induced in the two secondary windings. The frequency of the ac applied to the primary winding ranges from 50 Hz to 20 kHz.

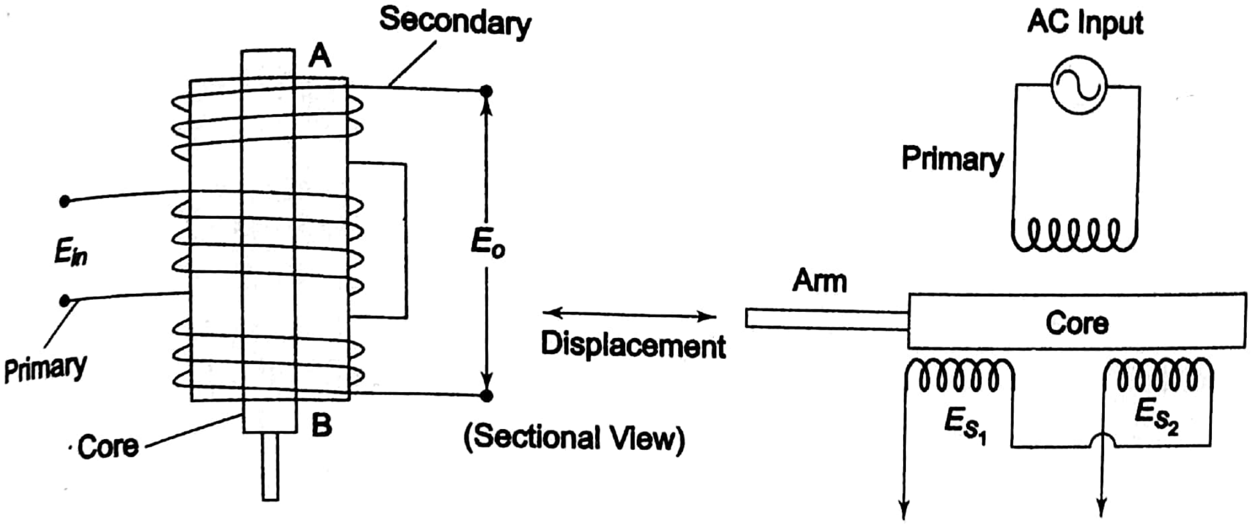
The output voltage of the secondary windings S_1 is E_{S1} and that of secondary winding S_2 is E_{S2}.

In order to convert the output from S_1 to S_2 into a single voltage signal, the two secondaries S_1 and S_2 are connected in series opposition, as shown in Fig. 13.20.

Hence the output voltage of the transducer is the difference of the two voltages. Therefore the differential output voltage $E_o = E_{S1} \sim E_{S2}$.

When the core is at its normal position, the flux linking with both secondary windings is equal, and hence equal emfs are induced in them. Hence, at null position $E_{S1} = E_{S2}$. Since the output voltage of the transducer is the difference of the two voltages, the output voltage E_o is zero at null position.

Now, if the core is moved to the left of the null position, more flux links with winding S and less with winding S of the secondary winding S_1 is greater than E_{S2}. The magnitude of the output voltage of the secondary is then $E_{S1} - E_{S2}$, in phase with E_{S1} (the output voltage of secondary winding S_1).



(a) Construction

(b) Basic Circuit

Fig. 13.20 Secondary winding connected for differential output

Similarly, if the core is moved to the right of the null position, the flux linking with winding S_2 becomes greater than that linked with winding S_1. This results in E_{S2} becoming larger than E_{S1}. The output voltage in this case is $E_o = E_{S2} - E_{S1}$ and is in phase with E_{S2}.

The amount of voltage change in either secondary winding is proportional to the amount of movement of the core. Hence, we have an indication of the amount of linear motion. By noting which output is increasing or decreasing, the direction of motion can be determined. The output ac voltage inverts as the core passes the centre position. The farther the core moves from the centre, the greater the difference in value between E_{S1} and E_{S2} and consequently the greater the value of E_o. Hence, the amplitude is function of the distance the core has moved, and the polarity or phase indicates the direction of motion, as shown in Fig. 13.21.

As the core is moved in one direction from the null position, the difference voltage, i.e. the difference of the two secondary voltages increases, while maintaining an in-phase relation with the voltage from the input source. In the other direction from the null position, the difference voltage increases but is 180° out of phase with the voltage from the source.

By comparing the magnitude and phase of the difference output voltage with that of the source, the amount and direction of the movement of the core and hence of the displacement may be determined.

The amount of output voltage may be measured to determine the displacement. The output signal may also be applied to a recorder or to a controller that can restore the moving system to its normal position.

The output voltage of an LVDT is a linear function of the core displacement within a limited range of motion (say 5 mm from the null position).

Figure 13.21(d) shows the variation of the output voltage against displacement for various position of the core. The curve is practically linear for small displacements (up to 5 mm). Beyond this range, the curve starts to deviate.

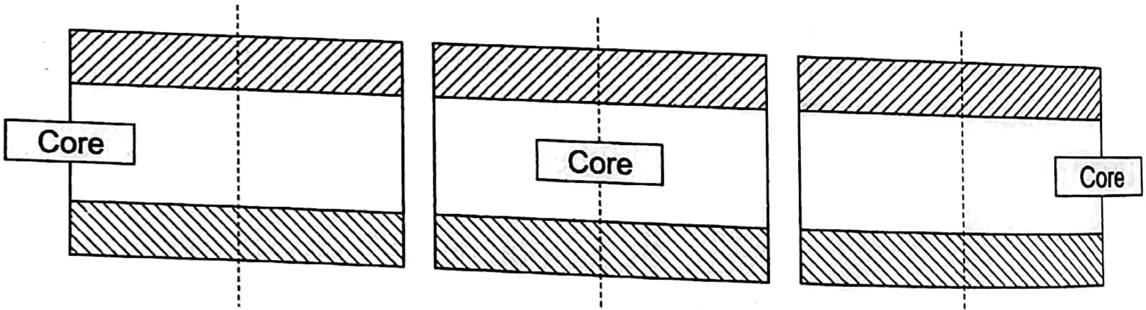
The diagram in Figs 13.21(a), (b) and (c) shows the core of an LVDT at three different positions.

In Fig. 13.21(b), the core is at O, which is the central zero or null position. Therefore, $E_{S1} = E_{S2}$ and $E_o = 0$.

When the core is moved to the left, as in Fig. 13.21(a) and is at A, E_{S1} is more than E_{S2} and E_o is positive. This movement represents a positive value and therefore the phase angle, is $\phi = 0°$.

When the core is moved to the right towards B, E_{S2} is greater than E_{S1} and hence E_o is negative. Therefore, S_2 the output voltage is 180° out of phase with the voltage which is obtained when the core is moved to the left. The characteristics are linear from $O - A$ and $O - B$, but after that they become non-linear.

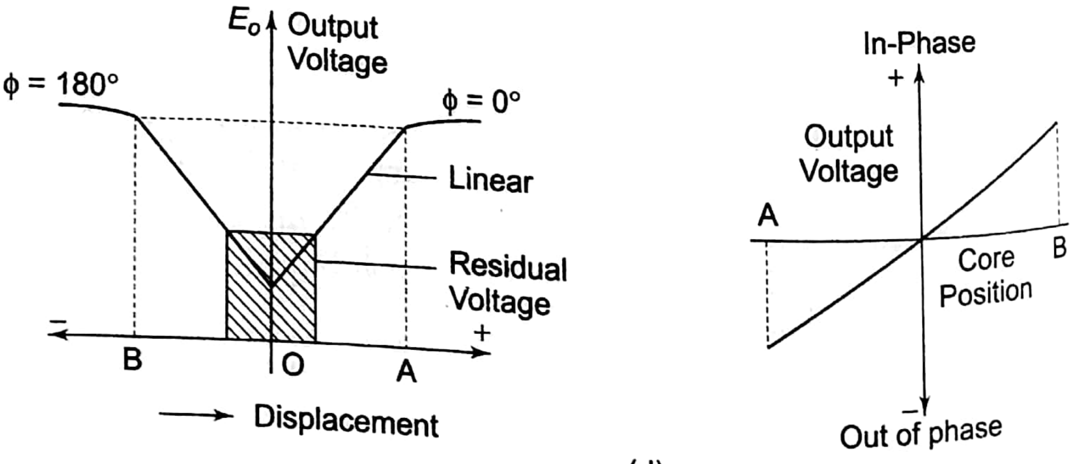
One advantage of an LVDT over the inductive bridge type is that it produces higher output voltage for small changes in core position. Several commercial models that produce 50 mV/mm to 300 mV/mm are available. 300 mV/mm implies that a 1 mm displacement of the core produces a voltage output of 300 mV.



Core at A
(a)

Core at O
(b)

Core at B
(c)



(d)

Fig. 13.21 (a), (b), (c) Various core position of LVDT
(d) Variation of output voltage vs displacement

LVDTs are available with ranges as low as ± 0.05 in. to as high as ± 25 in. and are sensitive enough to be used to measure displacements of well below 0.001

in. They can be obtained for operation at temperatures as low as – 265°C and as high as + 600°C and are also available in radiation resistance designs for nuclear operations.

Advantages of LVDT

1. ***Linearity*** The output voltage of this transducer is practically linear for displacements upto 5 mm (a linearity of 0.05% is available in commercial LVDTs).
2. ***Infinite resolution*** The change in output voltage is stepless. The effective resolution depends more on the test equipment than on the transducer.
3. ***High output*** It gives a high output (therefore there is frequently no need for intermediate amplification devices).
4. ***High sensitivity*** The transducer possesses a sensitivity as high as 40 V/mm.
5. ***Ruggedness*** These transducers can usually tolerate a high degree of vibration and shock.
6. ***Less friction*** There are no sliding contacts.
7. ***Low hysteresis*** This transducer has a low hysteresis, hence repeatability is excellent under all conditions.
8. ***Low power consumption*** Most LVDTs consume less than 1 W of power.

Disadvantages

1. Large displacements are required for appreciable differential output.
2. They are sensitive to stray magnetic fields (but shielding is possible).
3. The receiving instrument must be selected to operate on ac signals, or a demodulator network must be used if a dc output is required.
4. The dynamic response is limited mechanically by the mass of the core and electrically by the applied voltage.
5. Temperature also affects the transducer.

Example 13.6 *An ac LVDT has the following data.*

Input = 6.3 V, Output = 5.2 V, range ± 0.5 in. Determine

(i) *Calculate the output voltage vs core position for a core movement going from + 0.45 in. to – 0.30 in.*

(ii) *The output voltage when the core is – 0.25 in. from the centre.*

Solution

(i) 0.5 in. core displacement produces 5.2 V, therefore a 0.45 in. core movement produces (0.45 × 5.2)/0.5 = 4.68 V.

Similarly a – 0.30 in. core movement produces

$$(-0.30 \times -5.2)/(-0.5) = -3.12 \text{ V}$$

(ii) – 0.25 in. core movement produces

$$(-0.25 \times -5.2)/(-0.5) = -2.6 \text{ V}$$

13.11.1 Rotational Variable Differential Transducer (RVDT)

As seen previously, an LVDT is used to measure linear displacement. But when angular displacement is desired, a Rotational Variable Differential Transducer (RVDT) is used.

A Rotary Variable Differential Transformer (RVDT) is a type of electrical transformer used for measuring angular displacement.

More precisely, a Rotary Variable Differential Transformer (RVDT) is an electromechanical transducer that provides a variable alternating current (ac) output voltage that is linearly proportional to the angular displacement of its input shaft. When energized with a fixed ac source, the output signal is linear within a specified range over the angular displacement.

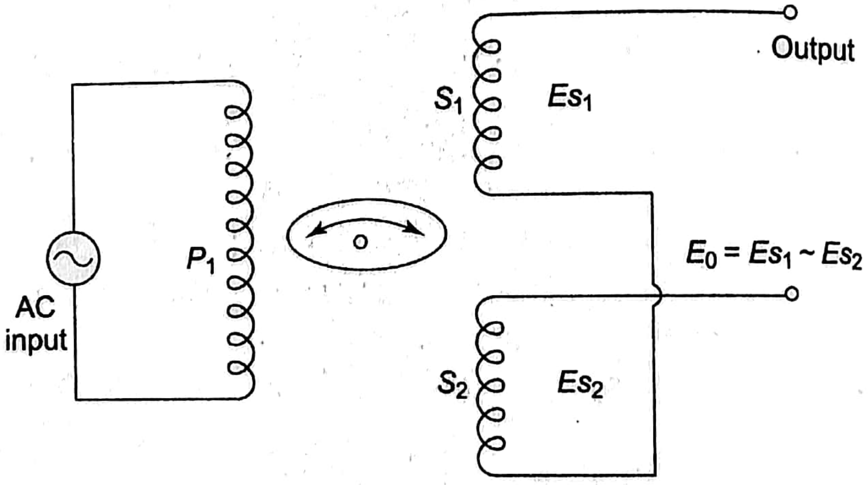


Fig 13.22 Rotational variable differential transducer

The RVDT is similar in construction to the LVDT, except that a cam-shaped core replaces the core in the LVDT as shown in Fig 13.22.

If the core is at the centre as in the case of LVDT, equal flux is linked with both secondary windings. Equal voltages are developed from the primary windings to the secondary windings. Hence the output being the differential output will be zero or null.

If the core is turned above the centre, the flux linking with one winding S_1, increases while the other S_2 decreases. Hence the output can be consider as a positive value.

If the core is turned in the other direction, the flux linking with winding S_1 reduces, while that linked with winding S_2 increases, hence producing an out of phase output that is in the opposite direction that is a negative value.

Hence the output gives the magnitude and direction of rotation. Hence angular displacement can be measured.

Most RVDT's are composed of a wound, laminated stator and a salient two-pole rotor. The stator, containing four slots, contains both the primary winding and the two secondary windings. Some secondary windings may also be connected together.

RVDT's utilize brushless, non-contacting technology to ensure long life and reliable, repeatable position sensing with infinite resolution. Such reliable and repeatable performance assures accurate position sensing under the most extreme operating conditions.

Operation of RVDTs The two induced voltages of the secondary windings, V_1 and V_2, varies linearly to the mechanical angle of the rotor, θ:
The difference $V_1 - V_2$ gives a proportional voltage:

$$\Delta V = 2 \cdot G \cdot \theta$$

and the sum of the voltages is a constant:

$$C - \Sigma V = 2 \cdot V_0$$

This constant gives the RVDT great stability of the angular information, independence of the input voltage or frequency, or temperature and enables it to also detect a malfunction.

Basic RVDT construction and operation is provided by rotating an iron-core bearing supported within a housed stator assembly. The housing is passivated stainless steel. The stator consists of a primary excitation coil and a pair of secondary output coils. A fixed alternating current excitation is applied to the primary stator coil that is electromagnetically coupled to the secondary coils. This coupling is proportional to the angle of the input shaft. The output pair is structured so that one coil is in-phase with the excitation coil, and the second is 180 degrees out-of-phase with the excitation coil. When the rotor is in a position that directs the available flux equally in both the in-phase and out-of-phase coils, the output voltages cancel and result in a zero value signal. This is referred to as the Electrical Zero position or EZ. When the rotor shaft is displaced from EZ, the resulting output signals have a magnitude and phase relationship proportional to the direction of rotation. Because RVDTs perform essentially like a transformer, excitation voltage changes will cause directly proportional changes to the output (transformation ratio). However, the voltage out to excitation voltage ratio will remain constant. Since most RVDT signal conditioning systems measure signal as a function of the Transformation Ratio (TR), excitation voltage drift beyond 7.5% typically has no effect on sensor accuracy and strict voltage regulation is not typically necessary. Excitation frequency should be controlled within +/– 1% to maintain accuracy

Although the RVDT can theoretically operate between ±45°, accuracy decreases quickly after ±35°. Thus, its operational limits lie mostly within ±30°, but some up to ±40°. Certain types can operate up to ±60°.

Advantages

- low sensitivity to temperature, primary voltage and frequency variations
- sturdiness
- relative low cost due to its popularity
- simple control electronics
- small size
- solid and robust, capable of working in a wide variety of environments

- No friction resistance, since the iron core does not contact the transformer coils, resulting in an very long service life
- High signal to noise ratio and low output impedance
- Negligible hysteresis
- Infinitesimal theoretical resolution; in reality, angle resolution is limited by the resolution of the amplifiers and voltage meters used to process the output signal
- No permanent damage to the RVDT if measurements exceed the designed range

Disadvantages The core must be in contact (directly or indirectly) with the measured surface which is not always possible or desirable.

Common Specifications Common specifications for commercially available RVDT's are listed below:

Input: Power input is a 3 to 15 V (rms) sine wave with a frequency between 60 to 20,000 Hz.

Angle: Capable of continuous rotational measurement. However, most RVDTs have effective angle limits of up to ±60°.

Nonlinearity: Higher accuracy in the smaller angle range: 0.25% @ ±30°, 0.50% @ ±40°, 1.50% @ ±60°.

PRESSURE INDUCTIVE TRANSDUCER 13.12

A simple, arrangement, wherein a change in the inductance of a sensing element is produced by a pressure change, is given in Fig. 13.23.

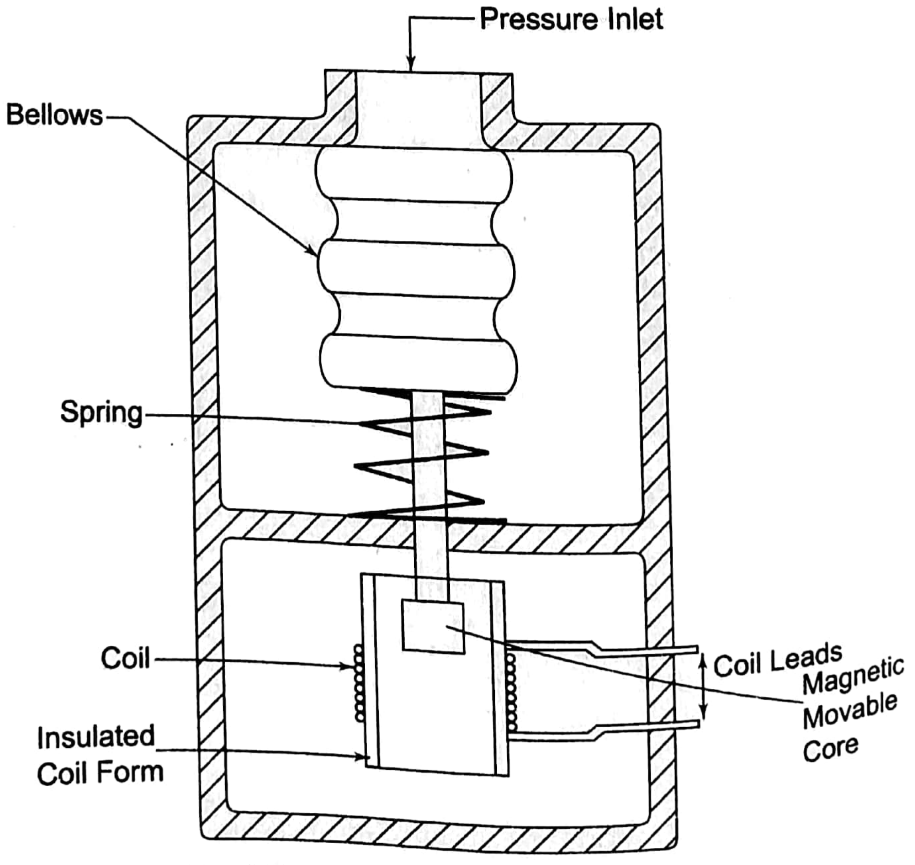


Fig. 13.23 Pressure inductive transducer

Here the pressure acting on a movable magnetic core causes an increase in the coil inductance corresponding to the acting pressure. The change in inductance can again be made on the basis of an electrical signal, using an ac bridge.

An advantage of the inductive type over the resistive type is that no moving contacts are present, thereby providing continuous resolution of the change, with no extra friction load imposed on the measuring system.

In a slightly modified form, this principle is used to obtain a change in mutual inductance between magnetically coupled coils, rather than in the self inductance of a single coil. When a change in an induced voltage is involved, the transducer is sometimes called a variable reluctance sensor or magnetic pickup. A very important example of the mutual type is the LVDT.

13.12.1 Inductive Position Transducers (Synchro's)

Synchro's is a generic name for a faculty of inductive devices which can be connected in various ways to form shaft angle measurement. All these devices work essentially on the same principle, that is of a rotating transformer. A Synchro appears like an AC motor consisting of a rotor and a stator.

Synchro's are normally used in control system, but have properties that can be used in instrumentation also.

A Synchro can be an angular position transducer working on inductive principle, wherein a variable coupling between primary and secondary winding is obtained by changing the relative orientation of the windings.

Internally, most synchro's are similar in construction. They have a rotor with one or three windings capable of revolving inside a fixed stator. There are two common types of rotors, the *salient pole* and the *wound rotor*.

The primary winding is a single phase winding wound on a rotor made of laminations. The connection to the rotor windings are made through precision slip rings shown in Fig. 13.24.

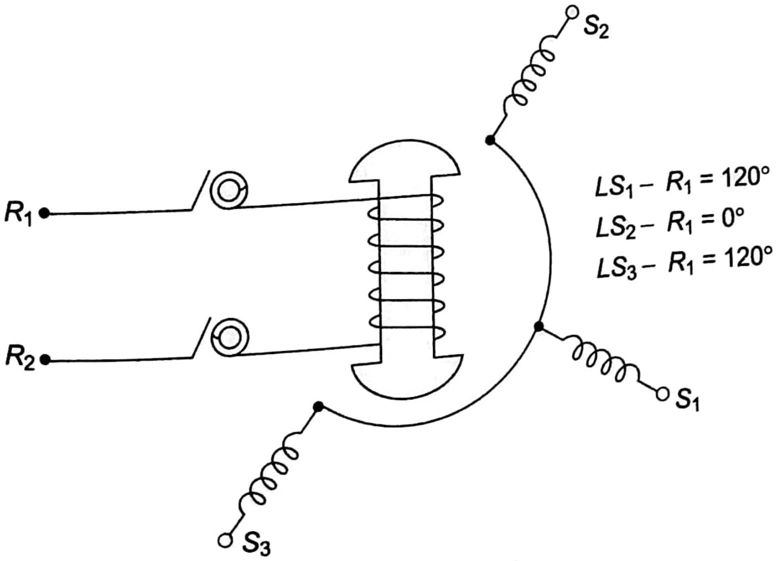


Fig. 13.24 Basic synchro

The stator has a 3-phase winding with the windings of the 3-phase displaced by 120°. The synchro may be viewed as a variable coupling transformer. A synchro is also called as *Selsyn*.

The rotor is energized by an ac voltage and coupling between rotor and stator windings varies as a trigonometric or linear function of the rotor position.

Synchro systems consists of two or more interconnected synchros. They are grouped or connected together according to the purpose to be used.

A Synchro system formed by interconnection of the devices called the Synchro transmitter and Synchro control transmitter is perhaps the most widely used error detector in feedback control system. It measures and compares two angular displacements and its output voltage is approximately linear with angular displacement.

The conventional Synchro transmitter (TX) uses a salient pole rotor with sleeved slot. When an ac excitation voltage is applied to the rotor, the resultant current produces a magnetic field and by transformer action induces voltages in the stator coils. The effective voltage induced in any stator coil depends upon the angular position of the coil axis with respect to the rotor axis (when the coil voltage is known, the induced voltage at any angular displacement can be determined).

Initially winding S_2 of the stator of transmitter is positioned for maximum coupling with the rotor winding as shown in Fig. 13.25(a). Suppose the voltage is V, the coupling between S_1 and S_2 of the stator and primary (rotor) winding is a cosine function. In general if the rotor is excited by 50 Hz ac, also called *reference voltage*, the voltage induced in any stator winding will be proportional to the cosine of the angle between the rotor axis and the stator axis. The voltages induced across any pair of stator terminals ($S_1 - S_2$, $S_1 - S_3$, or $S_2 - S_3$) will be sum or difference, depending on the phase of the voltage measured across the coils.

For example, if a reference voltage $V \sin \omega t$ excites the rotor of a synchro ($R_1 - R_2$), the stator terminals will have a voltage of the following form:

$$V(S_1 - S_2) = V \sin \omega t \sin \theta$$

$$V(S_1 - S_2) = V \sin \omega t \, (\sin \theta + 120°)$$

$$V(S_2 - S_3) = V \sin \omega t \, (\sin \theta + 240°)$$

where θ is the shaft angle.

These voltages are known as *Synchro format voltages*.

Therefore, the effective voltages in these windings are proportional to cos 60° or they are $V/2$ each. So long as the rotors of the transmitter and receiver remains in this position, no current will flow between the stator windings because of the voltage balance.

When the rotor of the transmitter is moved to a new position, the voltage balance is disturbed or changed. Assuming that the rotor of the transmitter is moved through 30° as shown in Fig. 13.25(b), the stator winding voltages of the transmitter will be changed to 0, $\sqrt{3/2}\,V$ and $\sqrt{3/2}\,V$ respectively.

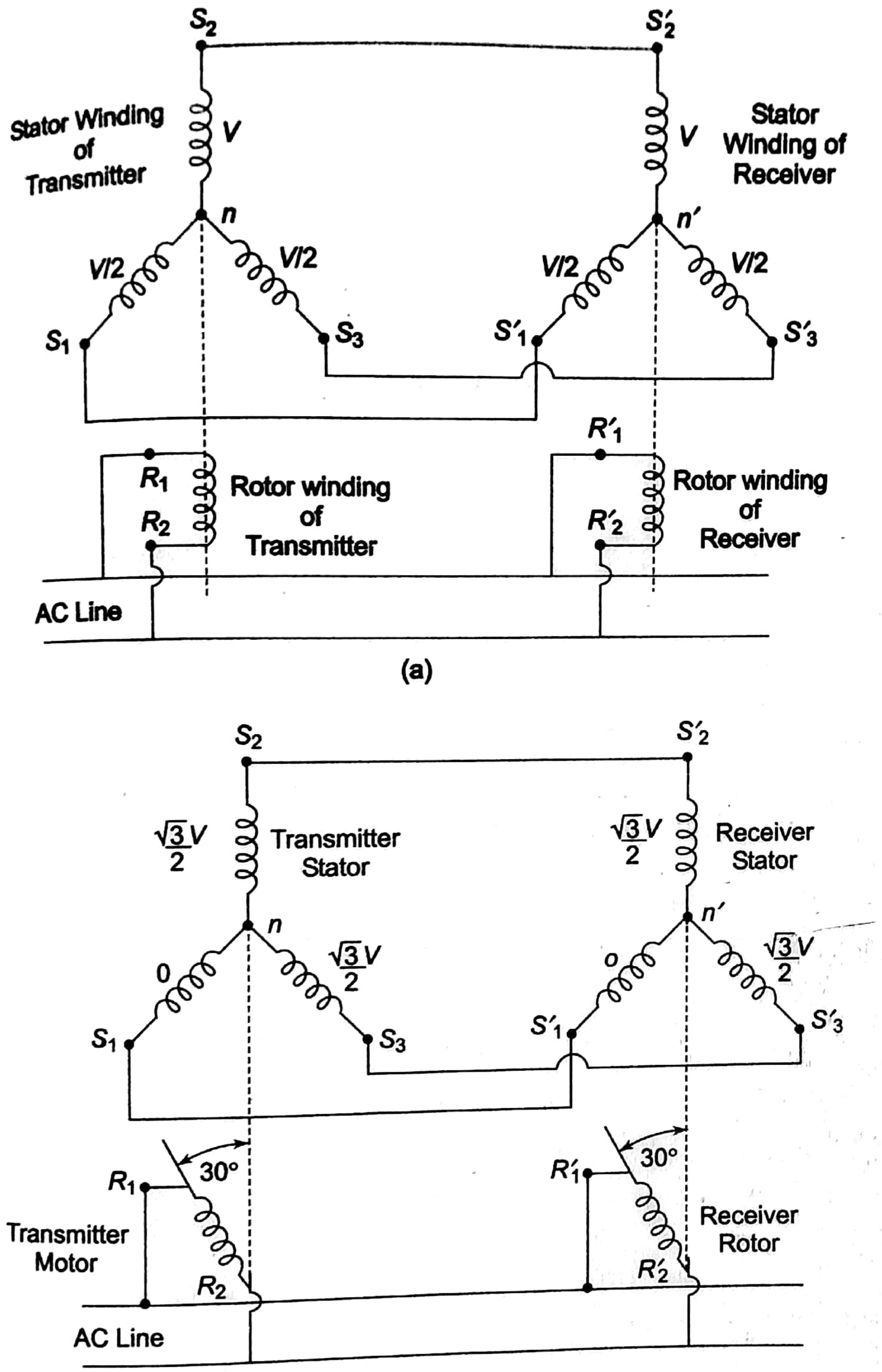


Fig. 13.25 (a) Torque transmission using synchro trans
(b) Follow up conditions of transmitter-receiver system

Hence, a voltage imbalance occurs between the stator windings of the transmitter and receiver. This voltage imbalance between the windings causes current to flow between the windings producing a torque that tends to rotate the rotor of the receiver to a new position where the voltage balance is again restored. This balance is restored only if the receiver turns through the same angle as the transmitter and also the direction of rotation is the same as that of the transmitter. Hence a Synchro can be used to determine the magnitude and direction of angular displacement.

Torque synchros are required if it is necessary to transmit angular displacement information from a shaft of one Synchro to the shaft of another Synchro without using any additional amplifiers or gears.

Torque synchro are commonly connected in repeater system consisting of torque transmitter and torque receiver. These repeater system is accurate to ± 1° and is used in systems in which a rotating devices output is required to position a remote pointer.

Today, most of these units have been replaced by a Syncrho-to-digital converter driving a LED display of the digital readout of angular position.

13.12.2 Selsyn

Synchros also called as Selsyn are motor like devices used to form position sensing and indicating system. Its principle is also based on the variation of mutual coupling between transmitter windings.

There are two types of Selsyn:

1. Torque type
2. Control type

Torque type of Selsyn consists of two rotors with a single winding and a stator with 3 windings distributed 120° apart. This section acts as a transmitter. The generator stator windings are connected to the other remotely located 3 phase windings. This section acts as a receiver and also has receiver rotor windings. The torque Selsyn is shown in Fig. 13.26.

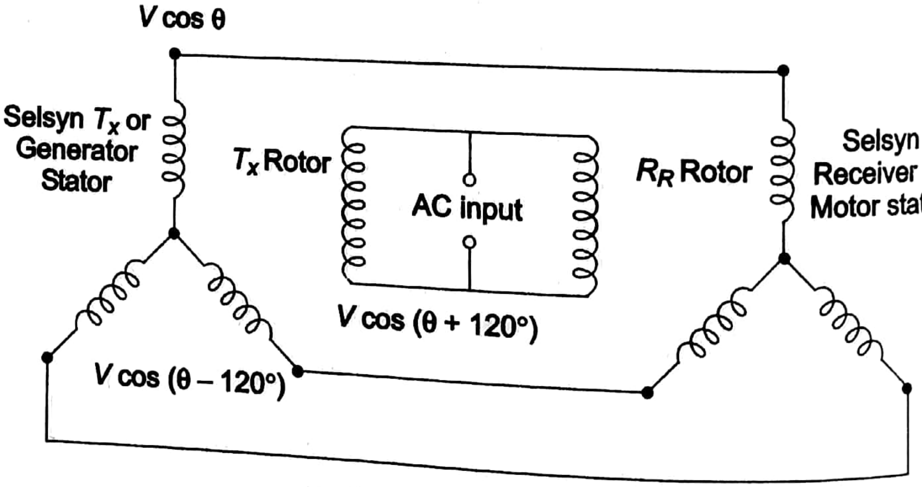


Fig. 13.26 Torque selsyn

The rotor of both units are excited through slip rings by an ac source at a convenient frequency.

If the receiver rotor is in the same relative position with reference to stator windings as the transmitter, the inductive coupling is identical and no stator current flows between the two units.

If transmitter rotor is shifted from this null position, voltages induced in the two stator will be the difference and a current starts to flow. This current flow produces a torque in the receiver which causes the receiver rotor to move into alignment with the new transmitter rotor position and the previous null position is obtained. Hence the receiver always follow the angular motion in accordance with that of the transmitter. Its accuracy is limited by the friction of the receiver bearings and calibration of its dial face.

13.12.3 Control Synchro

When larger amounts of power or torque and greater accuracy are required control synchros are used.

These devices are used for providing and handling control signals to a servo amplifier when more power and accurate angular displacement of a large load are required. The control synchros are not designed to handle any mechanical load.

The Control Transformer (CT) develops an ac rotor output voltage that is proportional to the relative shaft angles between synchro transmitter and control transformer. The devices are normally connected as shown in Fig. 13.27.

The two most common control synchro are Control Transmitter (CX) and Control Transformer (CT).

The output of the CX (transmitter) is fed to the stator of CT (transformer). The CT is a high impedance version of the torque receiver with its rotor aligned at 90° to that of transmitter (TR).

In a control system, when the shaft angle of the CX equals that of CT shaft angle, a minimum and null voltage will appear on the rotor terminals R_1 and R_2 of the CT. Any variation from this null will produce a signal in CT rotor whose phase will depend in which direction it is moved off the null.

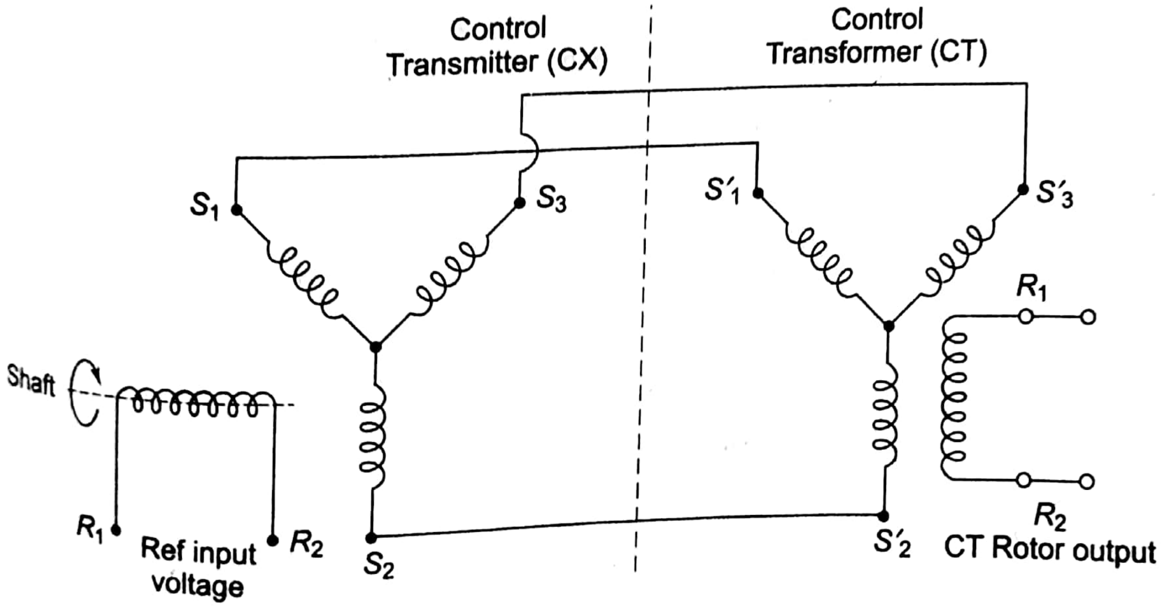


Fig. 13.27 Synchro control system

A simple closed loop servo system using a CX and CT control system is shown in Fig. 13.28.

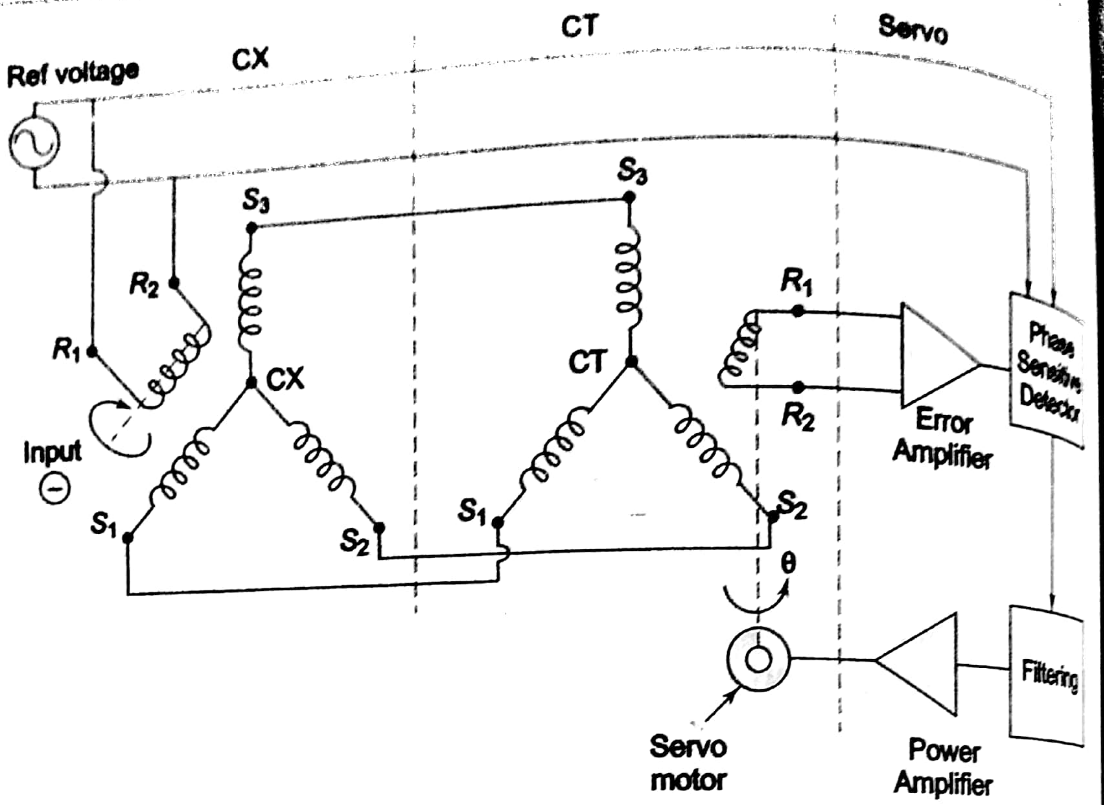


Fig. 13.28 Simple servo system using control synchro

When the shaft of the CX is turned to some angle θ, S_1, S_2 and S_3 output provide synchro format voltage as discussed previously. These voltages are transmitted to the CT stators S_1, S_2, S_3. If the CT is not at the input angle θ, a voltage will be produced at the output of the CT rotor winding. This signal (error) is amplified, phase detected and fed to a servo amplifier to cause a servo motor to position a load and the CT shaft to a position where the CT rotor output is minimum (null). The direction, in which the motor turns towards the angle θ, is determined by the phase of the CT rotor with respect to the reference voltage. Hence servo action takes place.

CAPACITIVE TRANSDUCER (PRESSURE) 13.13

A linear change in capacitance with changes in the physical position of the moving element may be used to provide an electrical indication of the element's position.

The capacitance is given by $C = KA/d$ (13.14)

where K = the dielectric constant

A = the total area of the capacitor surfaces

d = distance between two capacitive surfaces

C = the resultant capacitance.

From this equation, it is seen that capacitance increases (i) if the effective area of the plate is increased, and (ii) if the material has a high dielectric constant.

The capacitance is reduced if the spacing between the plates is increased.

Transducers which make use of these three methods of varying capacitance have been developed.

With proper calibration, each type yields a high degree of accuracy. Stray magnetic and capacitive effects may cause errors in the measurement produced, which can be avoided by proper shielding. Some capacitive dielectrics are temperature sensitive, so temperature variations should be minimised for accurate measurements.

A variable plate area transducer is made up of a fixed plate called Stator and a movable plate called the Rotor.

The rotor is mechanically coupled to the member under test. As the member moves, the rotor changes its position relative to the stator, thereby changing the effective area between the plates. A transducer of this type is shown in Fig. 13.29.

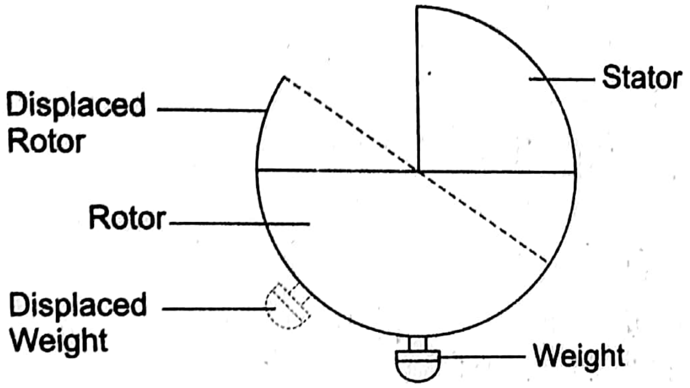


Fig. 13.29 Capacitive transducer

Such a device is used to detect the amount of roll in an aircraft. As the aircraft rolls to the left, the plates moves to the relative position shown by dashed lines in Fig. 13.29 and the capacitance decreases by an amount proportional to the degree of roll. Similarly to the right. In this case the stator, securely attached to the aircraft, is the moving element. The weight on the rotor keeps its position fixed with reference to the surface of the earth, but the relative position of the plates changes and this is the factor that determines the capacitance of the unit.

Figure 13.30 shows a transducer that makes use of the variation in capacitance resulting from a change in spacing between the plates. This particular transducer is designed to measure pressure (in vacuum).

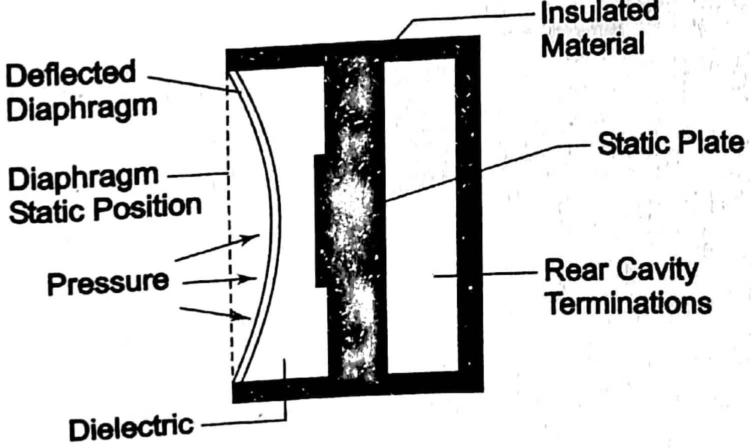


Fig. 13.30 Capacitive pressure transducer

Enclosed in an airtight container is a metallic diaphragm which moves to the left when pressure is applied to the chamber and to the right when vacuum is applied. This diaphragm is used as one plate of a variable capacitor. Its distance from the stationary plate to its left, as determined by the pressure applied to the unit, determines the capacitance between the two plates. The monitor indicates the pressure equivalent of the unit's capacitance by measuring the capacitor's reactance to the ac source voltage.

(The portion of the chamber to the left of the moving plate is isolated from the side into which the pressurised gas or vapour is introduced. Hence, the dielectric constant of the unit does not change for different types of pressurised gas or vapour. The capacity is purely a function of the diaphragm position.) This device is not linear.

Changes in pressure may be easily detected by the variation of capacity between a fixed plate and another plate free to move as the pressure changes. The resulting variation follows the basic capacity formula.

$$C = 0.885\,\frac{K(n-1)A}{t}\ \text{pf} \qquad (13.15)$$

where A = area of one side of one plate in cm^2
n = number of plates
t = thickness of dielectric in cm
K = dielectric constant

The capacitive transducer, as in the capacitive microphone, is simple to construct and inexpensive to produce. It is particularly effective for HF variations.

However, when the varying capacitance is made part of an ac bridge to produce an ac output signal, the conditions for resistive and reactive balance generally require much care to be taken against unwanted signal pickup in the high impedance circuit, and also compensation for temperature changes. As a result, the receiving instrument for the capacitive sensor usually calls for more advanced and complex design than is needed for other transducers.

LOAD CELL (PRESSURE CELL) 13.14

The load cell is used to weigh extremely heavy loads. A length of bar, usually steel, is used as the active element. The weight of the load applies a particular stress to the bar. The amount of strain which results in the bar for different values of applied stress is determined, so that the strain may be used as a direct measure of the stress causing it.

The load cell shown in Fig. 13.31 is a good example of the use of strain gauges in weighing operations.

As the stress is applied along the direction of S (shown by the arrow in Fig. 13.31), the steel bar experiences a compression along that axis and an expansion along the X and Y axes. As a result, gauge A experiences a decrease in resistance, while gauge B undergoes an increase in resistance. When these two gauges and the gauges on the two remaining sides of the steel are connected to form a bridge circuit, four times the sensitivity of a simple gauge bridge is obtained. This makes the load cell sensitive to very small values of applied stress, as well as to extremely heavy loads.

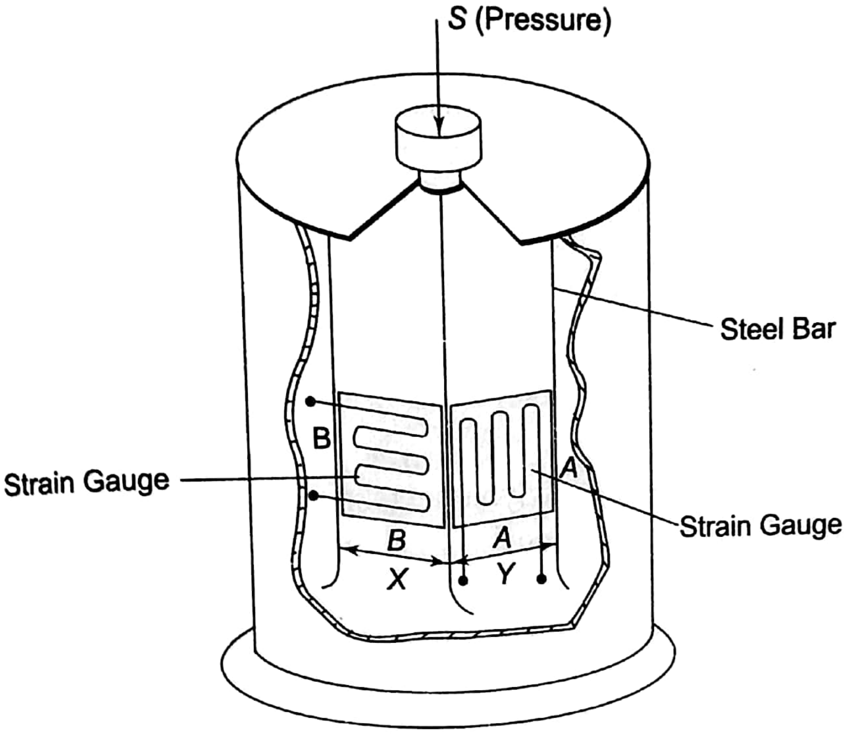


Fig. 13.31 Strain gauge load cell

13.15

PIEZO ELECTRICAL TRANSDUCER

A symmetrical crystalline materials such as Quartz, Rochelle salt and Barium titanate produce an emf when they are placed under stress. This property is used in piezo electric transducers, where a crystal is placed between a solid base and the force-summing member, as shown in Fig. 13.32.

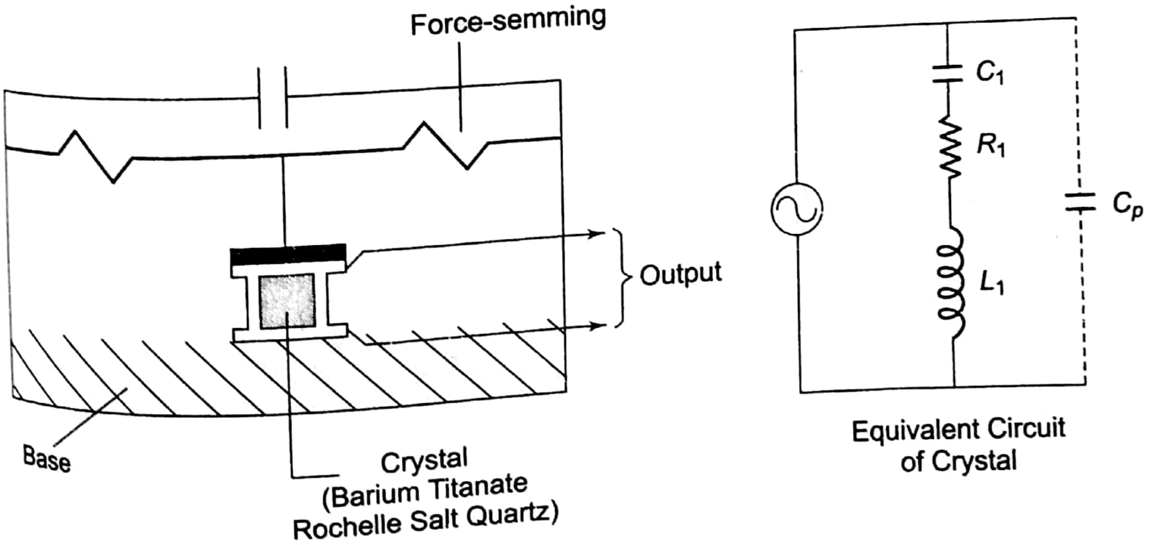


Fig. 13.32 Piezo electric transducer

An externally applied force, entering the transducer through its pressure port, applies pressure to the top of a crystal. This produces an emf across the crystal proportional to the magnitude of applied pressure.

Since the transducer has a very good HF response, its principal use is in HF accelerometers. In this application, its output voltage is typically of the order of 1 – 30 mV per gm of acceleration. The device needs no external power source and is therefore self generating. The disadvantage is that it cannot measure static conditions. The output voltage is also affected by temperature variation of the crystal. The basic expression for output voltage E is given by

$$E = \frac{Q}{C_p}$$

where Q = generated charge

C_p = shunt capacitances

This transducer is inherently a dynamic responding sensor and does not readily measure static conditions. (Since it is a high impedance element, it requires careful shielding and compensation.)

For a piezo electric element under pressure, part of the energy is converted to an electric potential that appears on opposite faces of the element, analogous to a charge on the plates of a capacitor. The rest of the applied energy is converted to mechanical energy, analogous to a compressed spring. When the pressure is removed, it returns to its original shape and loses its electric charge.

From these relationships, the following formulas have been derived for the coupling coefficient K.

$$K = \frac{\text{Mechanical energy converted to electrical energy}}{\text{Applied mechanical energy}}$$

or

$$K = \frac{\text{Electrical energy converted to mechanical energy}}{\text{Applied electrical energy}}$$

An alternating voltage applied to a crystal causes it to vibrate at its natural resonance frequency. Since the frequency is a very stable quantity, piezo electric crystals are principally used in HF accelerometers.

The principal disadvantage is that voltage will be generated as long as the pressure applied to the piezo electric element changes.

Example 13.7 *A certain crystal has a coupling coefficient of 0.32. How much electrical energy must be applied to produce an output of 1 oz.in. of mechanical energy?*

Solution

$$1 \text{ oz.in.} = 1 \text{ oz.in.} \times \frac{1 \text{ ft}}{12 \text{ in.}} \times \frac{1 \text{ lb}}{16 \text{ oz}} \times \frac{1.3561}{1 \text{ ft lb}}$$

$$= 7.06 \times 10^{-3} \text{ J}$$

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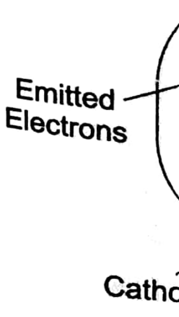

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dynode is at

$$\text{Applied Electrical energy} = \frac{\text{Electrical energy converted to mechanical energy}}{K}$$

$$= \frac{7.06 \times 10^{-3}}{0.32} = 22.19 \text{ mJ}$$

PHOTO ELECTRIC TRANSDUCER 13.16

Photo electric devices can be categorised as photo emissive, photo-conductive or photo-voltaic.

In photo emissive devices, radiation falling on a cathode causes electrons to be emitted from the cathode surface.

In photo conductive devices, the resistance of a material is changed when it is illuminated.

Photo voltaic cells generate an output voltage proportional to the radiation intensity. The incident radiation may be infrared, ultraviolet, gamma rays, X-rays, or visible light.

13.16.1 Photo Multiplier Tube

The photo multiplier tube consists of an evacuated glass envelope containing a photo cathode, an anode and several additional electrodes, termed Dynodes, each at a higher voltage, than the previous dynode.

Figure 13.33 illustrates the principle of the photo multiplier. Electrons emitted by the cathode are attracted to the first dynode. Here a phenomenon known as secondary emission takes place.

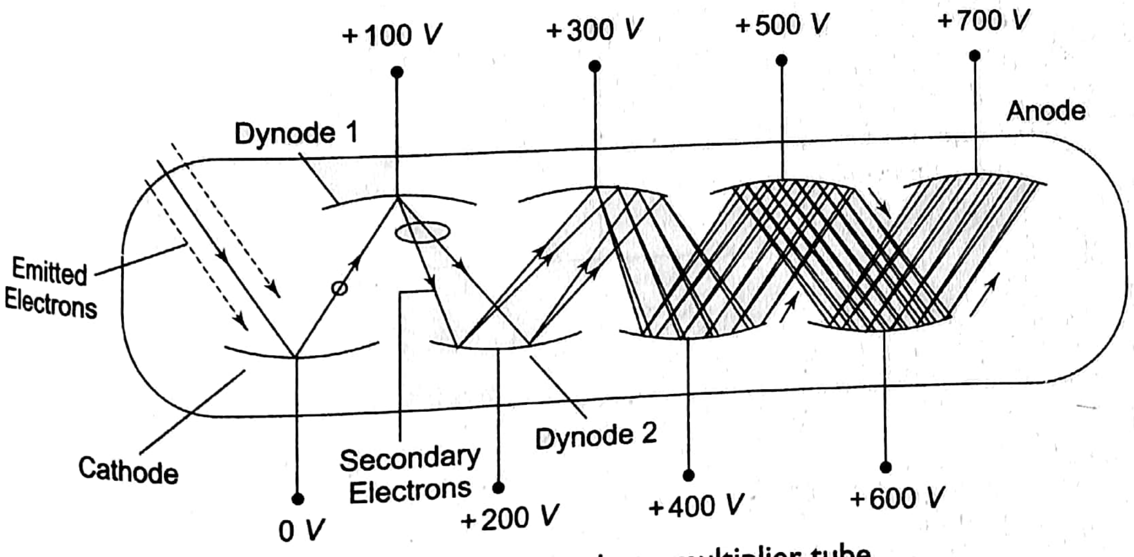


Fig. 13.33 Principle of a photo multiplier tube

When electrons moving at a high velocity strike an appropriate material, the material emits a greater number of electrons than it was struck with.

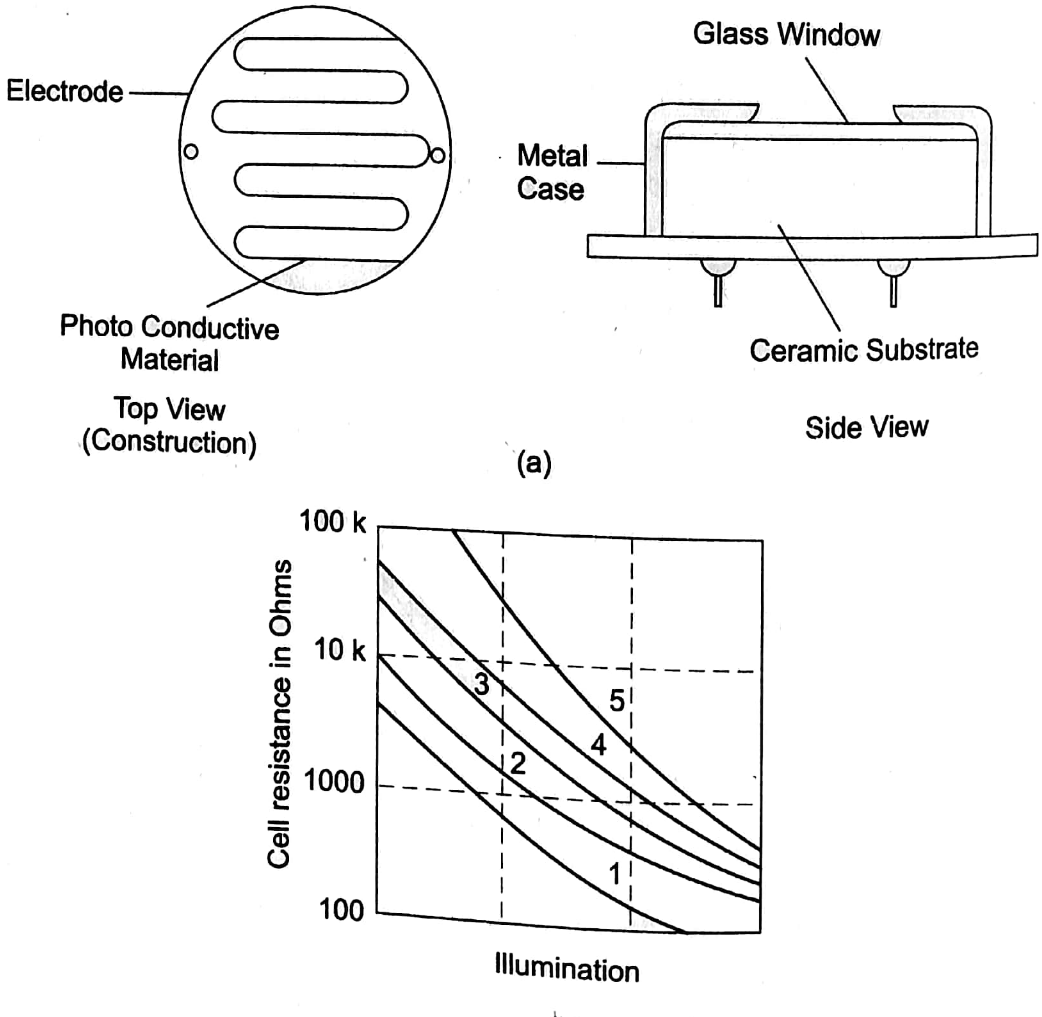
In this device, the high velocity is achieved by the use of a high voltage between the anode and the cathode. The electrons emitted by the first dynode are then attracted to the second dynode, where the same action takes place again. Each dynode is at a higher voltage, in order to achieve the requisite electron velocity each time. Hence, secondary emission, and a resulting electron multiplication, occurs at each step, with an overall increase in electron flow that may be very great. Amplification of the original current by much as $10^5 - 10^9$ is common. Luminous sensitivities range from 1A per lumen or less, to over 2000 A per lumen. Typical anode current ratings range from a minimum of 100 μA to a maximum of 1 mA.

The extreme luminous sensitivity possible with these devices is such that for a sensitivity of 100 A per lumen, only 10^{-5} lumen is needed to produce 1 mA of output current.

Magnetic fields affect the photo multiplier because some electrons may be deflected from their normal path between stages and therefore never reach a dynode or anode. Hence, the gain falls. To minimise this effect μ-metal magnetic shields are often placed around the photo multiplier tube.

13.16.2 Photo Conductive Cells or Photo Cells

The devices discussed above achieve an electrical output by photo emission. Another photo electric effect that is very useful is the photo conductive effect. In this effect, the electrical resistance of the material varies with the amount of incident light, as shown in Fig. 13.34(b).



(a)

(b)

Fig. 13.34 The photo conductive cell (a) construction (b) Typical curves of resistance vs illumination

A typical construction is as shown in Fig. 13.34(a). The photo conductive material, typically Cadium sulphide, Cadium selenide or Cadium sulpho-selenide, is deposited in a zig zag pattern (to obtain a desired resistance value and power rating) separating two metal coated areas acting as electrodes, all on an insulating base such as ceramic. The assembly is enclosed in a metal case with a glass window over the photo conductive material.

Photocells of these types are made in a wide range of sizes, from 1/8 in. in diameter to over 1 in. The small sizes are suitable where space is critical, as in punched card reading equipment. However, very small units have low power dissipation ratings.

A typical control circuit utilising a photo conductive cell is illustrated in Fig. 13.35. The potentiometer is used to make adjustments to compensate for manufacturing tolerances in photocells sensitivity and relay operating sensitivity.

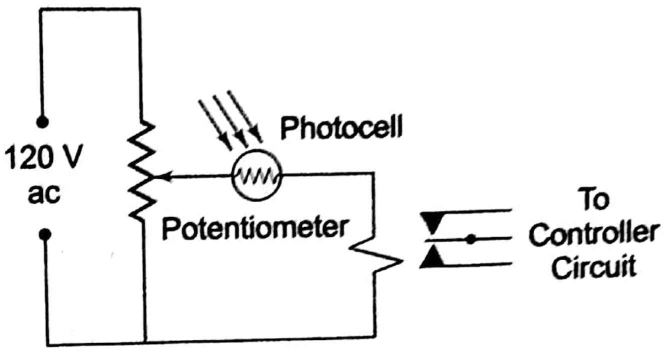


Fig. 13.35 Photo cell and relay control circuit

When the photocell has the appropriate light shining on it, its resistance is low and the current through the relay is consequently high enough to operate the relay. When the light is interrupted, the resistance rises, causing the relay current to decrease enough to de-energise the relay.

Example 13.8 (a) *The relay of Fig. Ex. 13.7(a) is to be controlled by a photo-conductive cell with the characteristics shown in Fig. Ex. 13.7(b). The potentiometer delivers 10 mA at a 30 V setting when the cell is illuminated with about 400 l/m² and is required to be de-energised when the cell is dark. Calculate (i) the required series resistance, and the (ii) dark current level.*

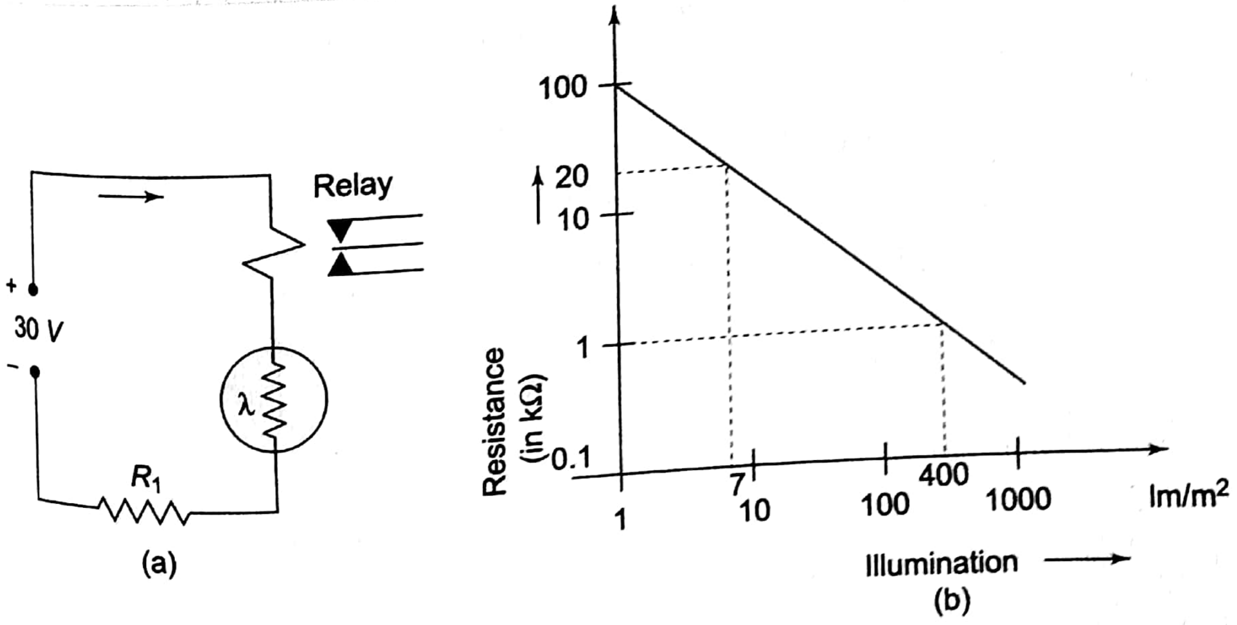


Fig. Ex. 13.7

Solution

(i) The cell resistance at 400 l/m^2 is 1 kΩ.

Therefore,
$$I = \frac{30\ V}{R_1 + R_{\text{cell}}} \quad \text{i.e.} \quad R_1 = \frac{30\ V}{I} - R_{\text{cell}}$$
$$= \frac{30\ V}{10\ \text{mA}} - 1\ \text{k} = 3\ \text{k} - 1\ \text{k} = 2\ \text{k}\Omega$$

(ii) The cells dark resistance is 100 kΩ

$$\text{Dark current} = \frac{30\ V}{2\ \text{k} + 100\ \text{k}} = \frac{30\ V}{102\ \text{k}} = 0.3\ \text{mA}$$

A typical use of this type of circuit is in counting objects, as on the conveyor belt of a production line. In this type of a circuit a beam of light traverses the path of the moving object that is on a conveyor belt. These objects have to be counted. Therefore, each time an object passes the beam is interrupted, and the relay actuates a counter.

PHOTO-VOLTAIC CELL

13.17

The photo-voltaic or solar cell, produces an electrical current when connected to a load. Both silicon (Si) and selenium (Se) types are known for these purposes.

Multiple unit silicon photo-voltaic devices may be used for sensing light in applications such as reading punched cards in the data processing industry.

Gold-doped germanium cells with controlled spectral response characteristics act as photo-voltaic devices in the infra-red region of the spectrum and may be used as infra-red detectors.

The silicon solar cell converts the radiant energy of the sun into electrical power. The solar cell consists of a thin slice of single crystal P-type silicon, up to 2 cm^2 into which a very thin (0.5 micron) layer of N-type material is diffused. The conversion efficiency depends on the spectral content and intensity of illumination.

SEMICONDUCTOR PHOTO DIODE

13.18

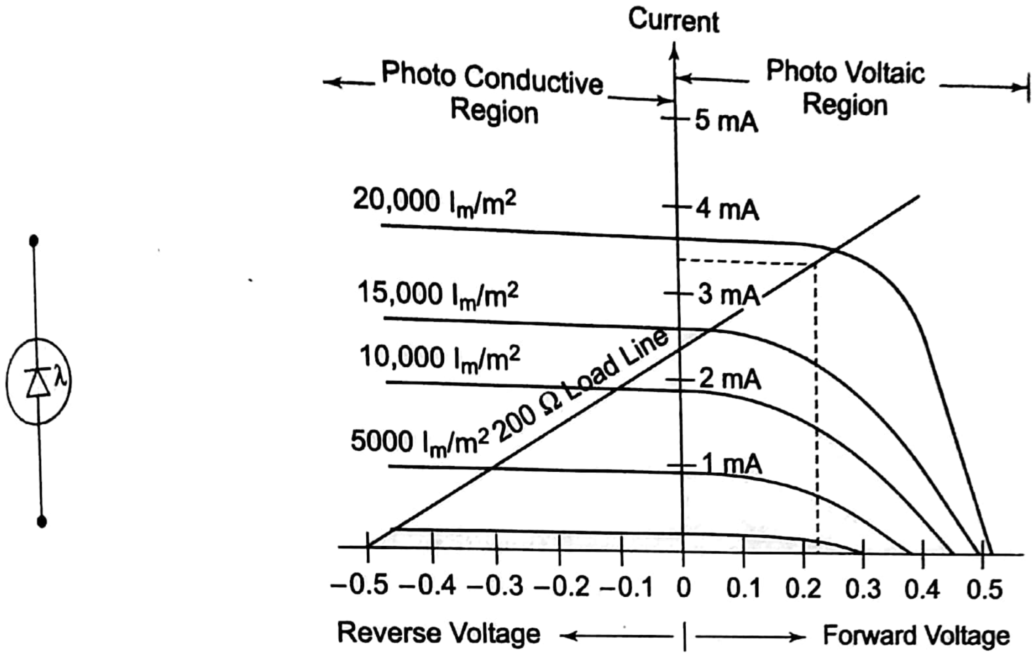
A reverse biased semiconductor diode passes only a very small leakage current (a fraction of 1 μA in silicon diodes), if the junction is exposed to light. Under illumination, however, the current rises almost in direct proportion to the light intensity. Hence, the photo-diode can be used for the same purposes as a photo-conductive cell.

This device, when operated with a reverse voltage applied, functions as a photo-conductive cell. When operated without reverse voltage it operates as a photo-voltaic cell.

A photo-diode can also be arranged to change from photo-conductive to photo-voltaic mode.

The response time of a photo-diode is very fast, so that it may be used in applications where light fluctuations occur at high frequency, but a photo-diode cell is useful only at very low frequencies.

The symbol and illumination characteristics are as shown in Figs. 13.36(a) and (b).

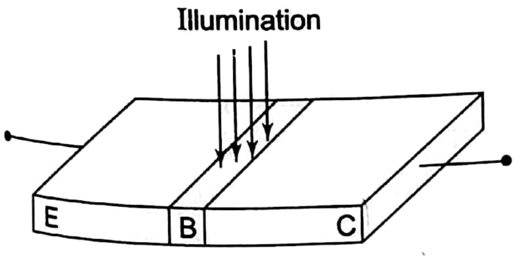


(a) (b)

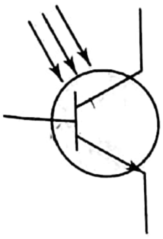
Fig. 13.36 (a) Photo diode symbol (b) Illumination characteristics

THE PHOTO-TRANSISTOR 13.19

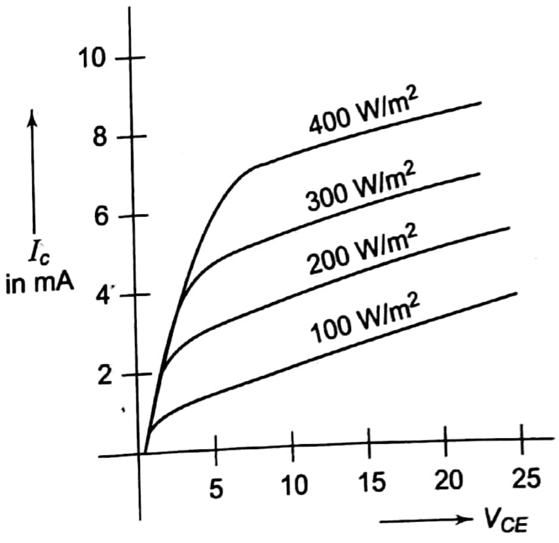
The sensitivity of a photo diode can be increased by as much as 100 times by adding a junction, resulting in an NPN device. A simple representation of the construction is shown in Fig. 13.37.



(a) Construction



(b) Symbol



(c) Output Characteristics

Fig. 13.37 Photo-transistor

Illumination of the central region causes the release of electron hole pa. This lowers the barrier potential across both junctions, causing an increase in t flow of electrons from the left region into the centre region and on to the rig region.

For a given amount of illumination on a very small area, the photo-transis provides a much larger output current than that available from a photo diode, i. a photo-transistor is more sensitive.

Arrays of transistors and low current photo diodes are widely used as pho detectors for such applications as punched card and tape readouts. Photo-transistors are more sensitive than photo-diodes, but the latter have a faster switching time.

One application of a photo-transistor is shown in Fig. 13.38.

The light incident on the photo-transistor causes its current to increase and therefore increases both the voltage drop across 50 kΩ and the input to the transistor which drives the relay. This raises the current to the operational level.

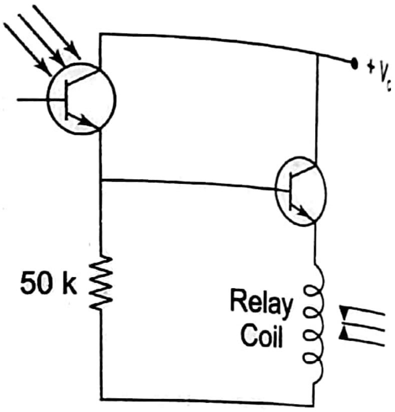


Fig. 13.38 Photo transistor and relay circuit

TEMPERATURE TRANSDUCERS 13.20

13.20.1 Introduction to Temperature Transducers

Temperature is one of the most widely measured and controlled variable in industry, as a lot of products during manufacturing requires controlled temperature at various stages of processing.

A wide variety of temperature transducers and temperature measurement systems have been developed for different applications requirements.

Most of the temperature transducers are of Resistance Temperature Detectors (RTD), Thermistors and Thermocouples. Of these RTD's and Thermistor are passive devices whose resistance changes with temperature hence need an electrical supply to give a voltage output. On the other hand thermocouples are active transducers and are based on the principle of generation of thermoelectricity, when two dissimilar metals are connected together to form a junction called the *sensing junction*, an emf is generated proportional to the temperature of the junction. Thermocouple operate on the principle of *seeback effect*. Thermocouple introduces errors and can be overcomed by using a reference junction compensation called as a *cold junction compensation*.

Thermocouples are available that span cryogenic to 2000°C temperature range. They have the highest speed of response. Thermocouples can be connected in series/parallel to obtain greater sensitivity called a *Thermopile*.

RTD commonly use platinum, Nickel or any resistance wire whose resistance varies with temperature and has a high intrinsic accuracy. Platinum is the most widely used RTD because of its high stability and large operating range. RTD's are usually connected in a Wheatstones bridge circuit. The lead wire used for connecting the RTD's introduces error, hence compensation is required. This is obtained by using three-wire or four wire compensation, but 3-wire compensation is mostly used in the industry.

Another form of temperature measurement is by the use of thermistor. A thermistor is a thermally sensitive resistor that exhibits change in electrical resistance with change in temperature. Thermistors made up of oxides exhibit a negative temperature coefficient (NTC), that is, their resistance decreases with increase in temperature. Thermistor are also available with positive temperature coefficient (PTC), but PTC thermistor are seldom used for measurement since they have poor sensitivity.

Thermistors are available in various sizes and shapes such as beads, rods, discs, washers and in the form of probes.

Radiation pyrometer are used where non-contact temperature is required to be measured. It measures the radiant (energy) heat emitted or reflected by a hot object. Radiation pyrometers are of two types total radiation pyrometer and infrared pyrometer.

Total radiation pyrometer virtually receives all the radiation from a heated body and measures temperature in the range around 1200°C–3500°C. Infrared pyrometers are partial or selective radiation pyrometers and are used in the range of 1000°C–1200°C.

Optical pyrometers are used in the visible wavelength. The most common type of optical pyrometer is the disappearing filament type and is used in temperature range of 1400°C and can be extended up to 3000°C. Optical pyrometers are widely used for accurate measurement of temperatures of furnaces, molten metals etc.

13.20.2 Resistance Temperature Detector (RTD)

Resistance temperature detector* commonly use platinum, nickel or any resistance wire whose resistance varies with temperature and which has a high intrinsic accuracy. They are available in many configuration and sizes; as shielded or open units for both immersion and surface applications.

The relationship between temperature and resistance of conductors in the temperature range near 0°C can be calculated using the equation

$$R_t = R_{\text{ref}}\,(1 + \alpha\Delta t) \qquad (13.16)$$

where
R_t = resistance of conductor at temperature t°C
R_{ref} = resistance of the reference temperature, usually 0°C
α = temperature coefficient of resistance
Δt = difference between operating and reference temperature

Almost all metals have a positive temperature coefficient (PTC) of resistance, so that their resistances increases with increase in temperature. Some materials, such as Carbon and Germanium have a negative temperature coefficient (NTC) of resistance.

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* Refer to section 13.7.

A high value of 'α' is desired in a temperature sensing element, so that sufficient change in resistance occurs for a relatively small change in temperature. This change in resistance (ΔR) can be measured with a Wheatstone's bridge which can be calibrated to indicate the temperature, that caused the resistance change rather than the resistance itself. The sensing element of the RTD is selected according to the intended applications.

RTD's are wire-wound resistance with moderate resistance and a PTC of resistance. Platinum is the most widely used resistance wire type because of its high stability and large operating range. However, Nickel and Copper are also used in RTDs. The temperature ranges for various resistance wire are given in Table 13.1.

Table 13.1

Platinum	– 200°C – 850°C
Copper	– 200°C – 260°C
Nickel	– 80°C – 300°C

Platinum RTDs provide high accuracy and stability. They have the following advantages:

1. Linearity over a wide operating range.
2. Wide operating range
3. Higher temperature operation
4. Better stability at high temperature

Disadvantages of RTD

1. Low sensitivity
2. It can be affected by contact resistance, shock and vibration
3. Requires no point sensing
4. Higher cost than other temperature transducers
5. Requires 3 or 4 wire for its operation and associated instrumentation to eliminate errors due to lead resistance

RTD's are not adaptable to applications requiring fast response or small area temperature sensing. Measurement of temperature using RTD is done after proper calibration that involves conversion of resistance value to temperature.

Most RTD instruments use a Wheatstone's Bridge or its modified version. The RTD and its leads are connected in one of its arms. This bridge is essentially a resistance measuring device which converts the resistance of the RTD into an electrical signal that is used for

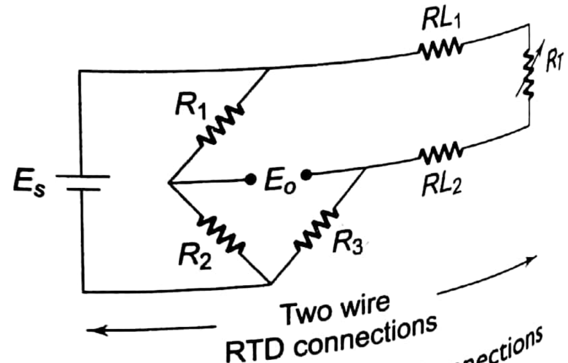

Fig. 13.39 Two wire RTD Connections

monitoring or controlling temperature. The basic Wheatstone's Bridge with a two wire RTD connected is as shown in Fig.13.39.

where E_s = Supply voltage
E_o = output voltage used for monitoring or controlling temperature
$R_1 - R_2$ and R_3 = fixed value resistors
R_T = resistance of temperature sensing element in RTD
RL_1 and RL_2 = resistance of the two leads connected in the RTD element

The value of R_T at the control point or at the mid point of the temperature range to be monitored will influence the arm resistors R_1, R_2 and R_3. Also, these values must be selected to limit bridge currents to avoid self-heating of RTD or bridge resistors. For achieving high accuracy, the bridge must be stable and insensitive to ambient temperature variations.

If the value of the lead resistance is small and also the variation of the lead resistance is small over the temperature range as compared to that of the RTD values, then the errors introduced by the lead resistance are not significant.

However, the errors introduced by long leads are significant and can be reduced by using thick lead wire. As an effective method to obtain a high degree of accuracy, it is desirable to use lead resistance compensation techniques or lead error elimination technique such as three wire and four wire RTD connections.

Two lead RTD which is lower in cost, is normally used when the lead resistance is low in comparison with Ohms/°C resistance change of the RTD or when lead wire resistance compensation is provided in the instrumentation.

Three Lead Wire RTD Three lead wire RTD, offers a practicable method for lead wire compensation that is sufficiently accurate for most industrial applications. The bridge circuit automatically compensates resistance change due to ambient temperature change, which is the input to the instrumentation. A three lead RTD connected to a Wheatstone Bridge circuit is as shown in Fig. 13.40.

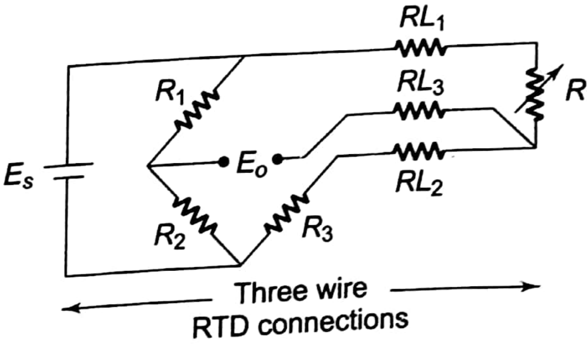

Fig. 13.40 Three wire RTD connections

This bridge circuit is used whenever lead wire resistance is significant in comparison with Ohms/°C sensitivity of the RTD elements, for example, the 10 Ω copper RTD element used in the industry should always have three leads. Other commonly used RTD elements such as 100 Ω platinum and 120 Ω Nickel may also need such compensation when lead wire resistance is significant.

Referring to Fig. 13.40, it can be seen that one of the RTD leads L_1 is in the arm of the bridge with R_T and a second lead L_2 is in the adjacent arm with R_3. When the bridge is balanced, all the bridge arm resistance are equal, hence same current flows in all the bridge arms. The same current flows through both these leads L_1 and L_2 under balance conditions, therefore the voltage drop across them will be identical and being in the adjacent arms will effectively cancel out. Hence the effect of the lead wire is eliminated.

The third lead L_3, is connected in the output circuit of the bridge and has no effect on the bridge ratios or balance. Hence when the bridge is balanced no current flows through L_3 and therefore has no effect on the bridge balance. This method gives very good accuracy if the lead resistances are matched.

Four Lead RTD Connection The three lead RTD gives sufficient accuracy for most of the industrial applications. However, when a higher degree of accuracy and precision is required, a four lead RTD connection is used.

The four lead RTD is the most expensive type, especially when long four wire extension leads are needed to connect to the instrumentation. However the four lead RTD can offer the greatest accuracy if the instrumentation is properly designed. Four lead RTDs are widely used in laboratory work, where highest precision is required.

To select a 100 Ω Platinum RTD, the information given in Table 13.2 is helpful.

Table 13.2

1.	Temperature range	200°C–850°C
2.	Temperature coefficient in %°C at 25°C	$\alpha = 0.39$
3.	Construction	Wire wound or thin film deposited platinum
4.	Self heating	0.02°C–0.75°C/mV (typical)
5.	Lead wire	Copper two, three or four depending on the system
6.	Lead resistance compensation	Use three or four wire lead systems
7.	Accuracy	± 0.6 at 100°C
8.	Resolution	0.29–0.39 Ω/°C
9.	Drift	Approximately 0.01–0.1°C per year

Example 13.8 (b) *A platinum resistance thermometer has a resistance of 180 Ω at 20°C. Calculate its resistance at 60°C ($\alpha_{20} = 0.00392$)*

Solution Given $R = R_o\,(1 - \alpha\,\Delta T)$

$$R = 180\,[1 - 0.00392\,(60°\text{C} - 20°\text{C}\,)]$$
$$R = 180\,[1 - 0.00392 \times 40°\text{C}\,)]$$
$$R = 180\,[1 - 0.1568]$$
$$R = 180 \times 0.8432$$
$$R = 151.78\ \Omega$$

Example 13.9 *A platinum resistance thermometer has a resistance of 100 Ω at 25°C. Find its resistance at 50°C. The resistance temperature coefficient of platinum is 0.00392 Ω/Ω°C.*

If the thermometer has a resistance of 200 Ω, calculate the value of temperature.

Solution
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Solution

Step 1: Using the linear approximations, the value of resistance at any temperature is given by,

$$R = R_0 (1 + \alpha_0 \Delta t)$$
$$R = 100(1 + [(0.00392) \times (50 - 25)°C])$$
$$= 100(1 + [(0.00392 \times 25)\ °C])$$
$$= 109.8\ \Omega$$

Step 2: Suppose t_2 is the unknown temperature then

$$200 = 100(1 + [(0.00392) \times (t_2 - 25)°C])$$
$$2 = (1 + [(0.00392) \times (t_2 - 25)\ °C])$$
$$2 - 1 = [(0.00392) \times (t_2 - 25)°C])$$
$$(t_2 - 25)°C = \frac{1}{0.00392} \quad \text{therefore, } t_2 = 280°C$$

13.20.3 Platinum Thin Film Sensors

Platinum thin film sensors are manufactured by a very thin layer of platinum in suitable pattern to achieve smaller dimension and higher resistance, on a ceramic base. The deposition of layers and introduction of patterns are obtained using different methods.

Normally, a number of such chips are manufactured on a single large substrate and the chips are properly cut and proper contacts are made. This platinum layer is usually coated with suitable material depending on the operating range to provide protection against mechanical and chemical damages.

The advantage of thin film sensors is reduction in the size and simultaneous increase in the nominal resistance. The response time is reduced by nearly 10 times or more because of the reduction in size. By using such a type of sensor, it is possible to manufacture a probe with a stainless steel sheath of 2 mm diameter.

The sensitivity of the sensor also increases with increase in nominal resistance. The small dimension of thin film platinum sensors allows temperature measurements in very small areas with a much higher accuracy as compared to the thermocouple.

Thin film sensors are cheaper to manufacture than wire wound RTDs, hence can be used in many fields of application for resistance thermometers such as automobiles, medical thermometer, etc.

13.20.4 Resistance Thermometer

The resistance of a conductor changes when its temperature is changed. This property is used for measurement of temperature. The resistance thermometer uses the change in electrical resistance of conductor to determine the temperature.

The requirements of a conductor material to be used in these thermometers are:

1. The change in resistance of material per unit change in temperature must be as large as possible.

2. The resistance of the material must have a continuous and stab relationship with temperature.

The main section of a resistance thermometer is its sensing element. Th characteristics of the sensing element, determines the sensitivity and operati temperature range of the instrument.

The sensing element may be any material that exhibits a relatively larg resistance change with the change in temperature. The material used should als have a stable characteristics, that is, neither its resistance nor its temperature coefficient of resistance should undergo permanent change with use or age.

It is necessary to consider stability in order to maintain the calibration of a resistance thermometer. The need for stability frequently limits the temperature range over which the sensing element may be used.

Another desirable characteristics for a sensing element is a linear change in resistance with change in temperature.

When the measured temperature is subjected to rapid variations, the speed with which a resistive element responds to changes in temperature is important. The smaller a given sensing element, less heat is required to raise its temperature, the faster is its response.

Platinum, Nickel and Copper are the metals most commonly used to measure temperature. The resistivity of platinum tends to increase less rapidly at higher temperatures than for other materials, hence it is a commonly used material for resistance thermometers. The temperature range over which Platinum has stability is 260 °C–1100 °C. An industrial Platinum resistance thermometer is as shown in Fig.13.41 (a).

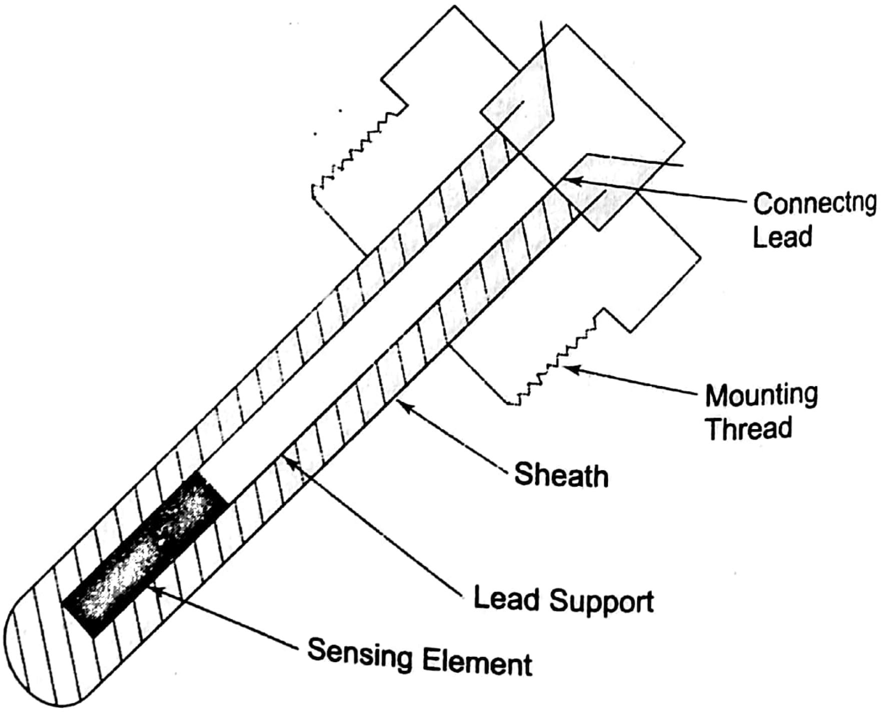


Fig. 13.41 (a) Industrial platinum ressistance thermometer

The changes in resistance caused by changes in temperature as detected by a Wheatstone's Bridge is shown in Fig. 13.41(b).

Hence, the temperature sensing element, which may be Nickel, Copper or Platinum contained in a bulb or well, along with the balancing bridge, forms the basic important components of a temperature measuring system based on this principle.

The sensing element R_s is made of a material having a high temperature coefficient, R_1, R_2 and R_5 are made of resistance that are practically constant under normal temperature changes.

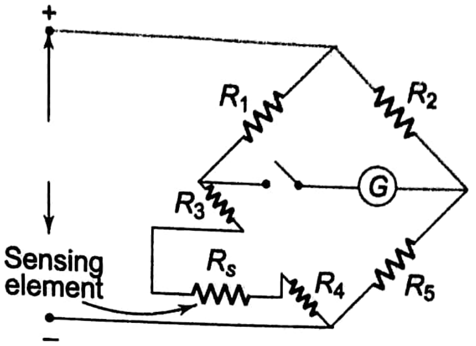


Fig.13.41 (b) Resistance thermometer connected in a bridge circuit

When the sensing element is very near the bridge, and under balance conditions, the following relationship holds good.

$$\frac{R_1}{R_2} = \frac{R_s}{R_5}$$

In normal practice, the sensing element is away from the indicator and the bridge, and its leads have a resistance, say R_3, R_4.

$$\therefore \qquad \frac{R_1}{R_2} = \frac{R_s + R_3 + R_4}{R_5}$$

When resistance R_s changes, the bridge balance is upset and the galvanometer shows a deflection, which can be calibrated to give a suitable temperature scale.

Advantages of Resistance Thermometers The measurement of temperature by the electrical resistance method has the following advantages and characteristics.

1. The measurement is very accurate.
2. Indicators, recorders and controllers can also be operated.
3. More than one resistance element can be clubbed to the same indicating/recording instrument.
4. The temperature resistance element can be easily installed and replaced.
5. The accuracy of the measuring circuit can be easily checked by substituting a standard resistor for the resistive element.
6. Resistive elements can be used to measure differential temperature.
7. Resistance thermometer have a wide working range without loss of accuracy, and can be used for temperature ranges (–200°C–650°C)
8. They are best suited for remote sensing and indication.
9. The response time of the resistive element is 2–10 s.
10. The error of the resistive element is in the range of ± 0.25% of the scale reading.
11. The size of the resistive element may be about 6–12 mm in diameter.
12. No necessity of temperature compensation.

13. Extremely accurate temperature sensing.
14. Performance stability over longer periods of time

Limitations of Resistance Thermometer

1. High cost
2. Need for bridge and power source
3. Possibility of self heating.

13.20.5 Thermistors

We have already discussed thermistors in detail in Sec. 13.8.

13.20.6 Thermocouple

One of the most commonly used methods of measurement of moderately high temperature is the thermocouple effect. When a pair of wires made up of different metals is joined together at one end, a temperature difference between the two ends of the wire produces a voltage between the two wires as illustrated in Fig. 13.42

Temperature measurement with Thermocouple is based on the Seebeck effect. A current will circulate around a loop made up of two dissimilar metal when the two junctions are at different temperatures as shown in Fig. 13.43.

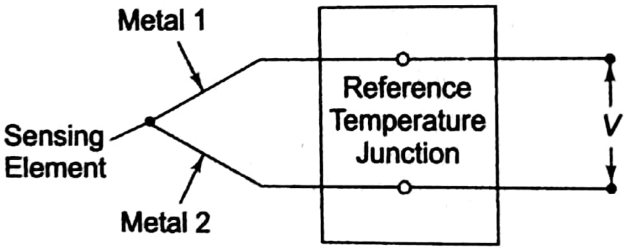


Fig. 13.42 Basic Thermocouple Connection

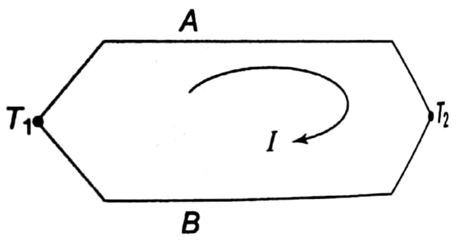


Fig. 13.43 Current through two dissimilar Metals

When this circuit is opened, a voltage appears that is proportional to the observed seebeck current.

There are four voltage sources, their sum is the observed seebeck voltage. Each junction is a voltage source, known as *Peltier emf.* Furthermore, each homogenous conductor has a self induced voltage or Thomson emf.

The Thomson and Peltier emfs originate from the fact that, within conductors, the density of free charge carriers (electrons and holes) increases with temperature.

(If the temperature of one end of a conductor is raised above that of the other end, excess electrons from the hot end will diffuse to the cold end. This results in an induced voltage, the *Thomson effect*, that makes the hot end positive with respect to the cold end.

Conductors made up of different materials have different free-carriers densities even when at the same temperature. When two dissimilar conductors are joined, electrons will diffuse across the junction from the conductor with higher electron density. When this happens the conductor losing electrons acquire a positive voltage with respect to the other conductor. This voltage is called the *Peltier emf.*)

When the junction is heated a voltage is generated, this is known as seebeck effect. The seebeck voltage is linearly proportional for small changes in temperature. Various combinations of metals are used in Thermocouple's.

The magnitude of this voltage depends on the material used for the wires and the amount of temperature difference between the joined ends and the other ends. The junction of the wires of the thermocouple is called the *sensing junction,* and this junction is normally placed in or on the unit under test.

Since it is the temperature difference between the sensing junction and the other ends that is the critical factor, the other ends are either kept at a constant reference temperature, or in the case of very low cost equipment at room temperature. In the latter case, the room temperature is monitored and thermocouple output voltage readings are corrected for any changes in it.

Because the temperature at this end of the thermocouple wire is a reference temperature, this function is known as the reference, also called as the *cold junction.*

A thermocouple, therefore consists of a pair of dissimilar metal wires joined together at one end (sensing or hot junction) and terminated at the other end (reference or cold junction), which is maintained at a known constant temperature (reference temperature). When a temperature difference exists between the sensing junction and the reference junction, an emf is produced, which causes current in the circuit.

When the reference end is terminated by a meter or a recording device, the meter indication will be proportional to the temperature difference between the hot junction and the reference junction.

The magnitude of the thermal emf depends on the wire materials used and in the temperature difference between the junctions.

Figure 13.44 shows the thermal emfs for some common thermocouple materials. The values shown are based on a reference temperature of 32°F.

The thermpcouple (TC) is a temperature transducer that develops an emf that is a function of the temperature difference between its hot and cold junctions.

A thermocouple may be regarded as a thermometer based on thermo-emf and works on the principle that the potential between two dissimilar metals or metal alloys is a function of temperature.

Type **'E'** Thermocouple units use Chromel alloy as the positive electrode and constantan alloy as the negative electrode.

Type **'S'** Thermocouple produces the least output voltage but can be used over greatest temperature range.

Type **'T'** shown in Fig. 13.45, uses copper and constantan.

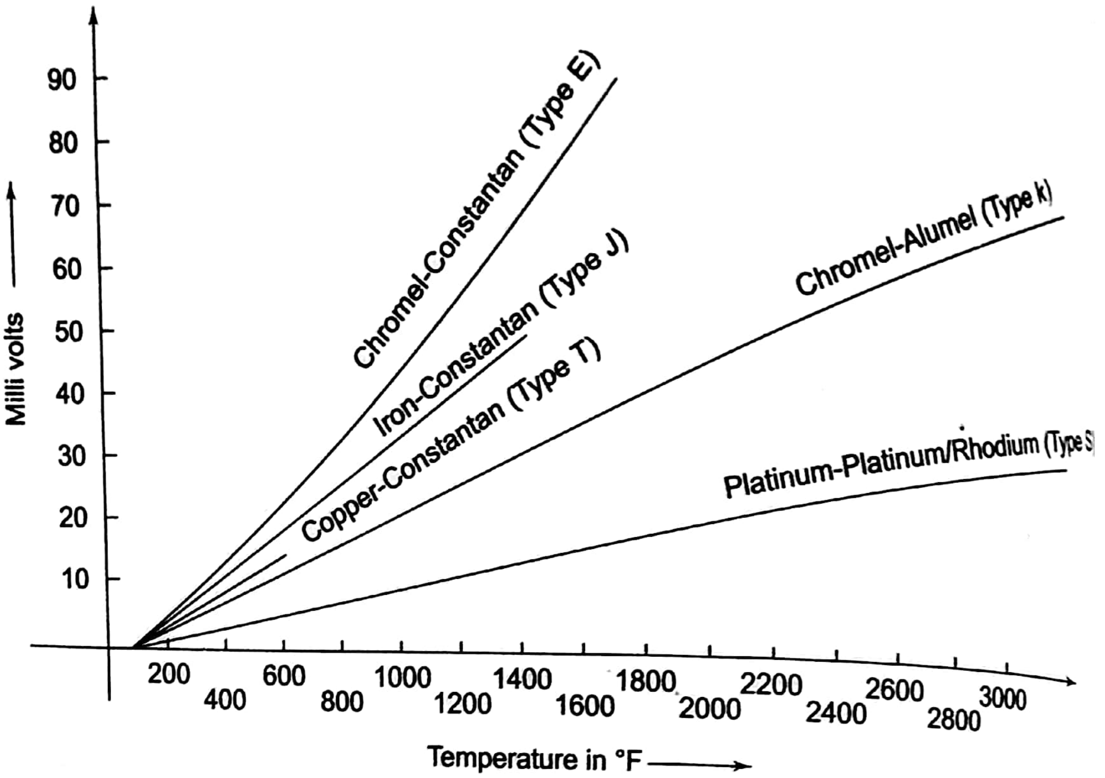


Fig. 13.44 Thermocouple output voltage as a function of temperature for various thermocouple materials

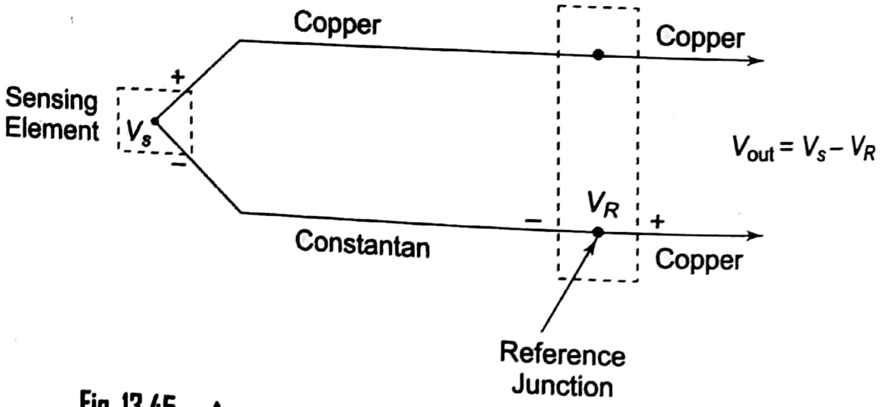


Fig. 13.45 A type t thermocouple with reference junction

Copper used, is an element and constantan used is an alloy of nickel and copper. The copper side is positive and constantan side is negative. Assuming copper wires used to connect the thermocouple to the next stage (circuit), a second Copper-Constantan junction is (formed) produced. This junction is called as the reference junction. It generates a Seebeck voltage that opposes the voltage generated by the sensing junction. If both junctions are at the same temperature, the output voltage V_{out} will be zero. If the sensing junction is at a higher temperature, V_{out} will be proportional to the difference between the two junction temperature. The temperature cannot be derived directly from the output voltage alone. It is subjected to an error caused by the voltage produced by the reference junction. This can be overcome by placing the reference junction in an ice bath to keep it at a known temperature. This process is called as *cold junction* *compensation* as shown in Fig.13.46(a). The reference voltage is maintained at 0°C. The reference voltage is now predictable from the calibration curve of the type 'T' thermocouple.

When copper is not one of thermocouple metal then four junction circuit is formed. The type 'J' thermocouple uses iron and constantan as the two elements shown in Fig.13.46(b). When it is connected to copper wires, two iron copper junctions result. These junctions present no additional difficulties because of the *isothermal block* used. This block is made of material that is a poor conductor of electricity but a good conductor of heat. Both Iron–Copper junctions will be at the same temperature and generate the same Seeback voltage and hence these two voltages will cancel. Cold junction compensation is also used as the Reference junction in this case.

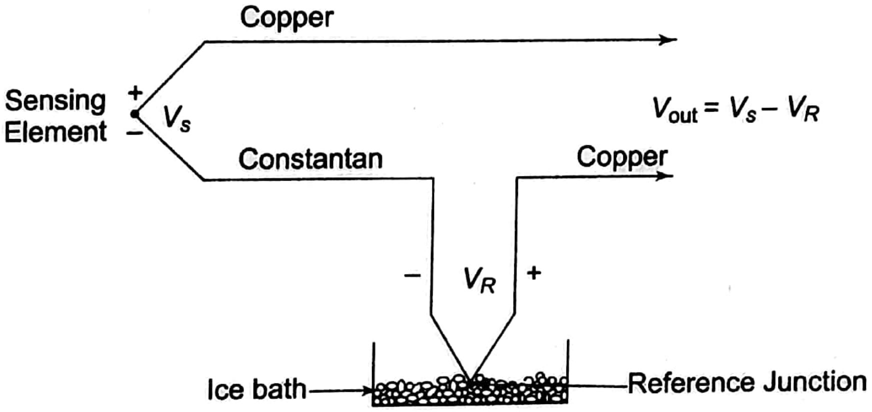


Fig. 13.46 (a) Cold junction compensation

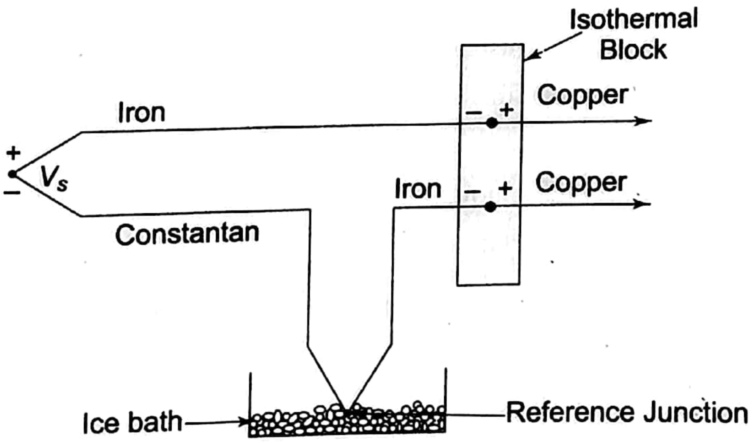


Fig. 13.46 (b) Type J thermocouple using isothermal block

The ice-baths method is not the most convenient method, to compensate the reference junction. This technique is often used in the calibration laboratory. Industry uses a different method of reference junction compensation as shown in Fig.13.47.

The isothermal block contains two reference junctions and a thermistor. The resistance of the thermistor is a function of temperature. A circuit is used to sense this resistance and to compensate for the voltage introduced by the two reference junctions. This arrangement is sometimes called as *Electronic ice point reference*.

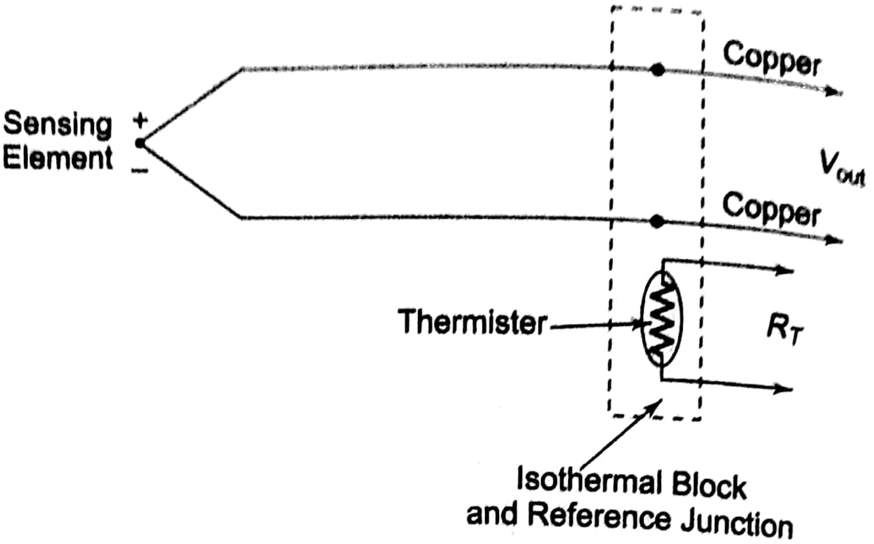


Fig. 13.47 Reference junction compensation used in industry

If the sensor is interfaced to a computer, the reference temperature will be converted to a reference voltage and then subtracted from the output voltage V_{out}. This process is known as *Software Compensation.*

An isothermal block with one temperature sensor can provide compensation for several units.

Table 13.3 gives the construction and thermoelectric properties of various thermocouples.

Table 13.3 Different Types of Thermocouples

Thermocouple type	*Materials used*	*Temperature range/ °C*	*Sensitivity μV/ °C*
Type T	Copper/Constantan	–200–400	15–60
E	Chromel/Constantan	0–850	40–55
J	Iron / Constantan	–200–900	45–57
K	Chromel/Alumel	–200–1250	40–55
R	Platinum/Platinum 13% Rhodium	0–1600	5–12
S	Platinum/Platinum 10% Rhodium	0–1500	5–12
B	Platinum 6% Rhodium/ Platinum 30% Rhodium	30–1800	0.3–0.8
G	Tungsten/Tungsten 26% Rhenium	15–2800	3–20
C	Tungsten 5% Rhenium/ Tungsten 25% Rhenium	0–2750	10–20

For accurate measurement of hot junction temperature, the cold junction or the reference junction should be kept at 0 °C. If the reference junction is kept at the ambient temperature, then a voltage corresponding to this temperature must be added to the measurement to obtain accurate reading.

Most modern thermocouple measurement systems employ electrical cold junction (an electronic circuit which simulates the voltage that the reference junction would generate at ambient temperature) compensation. A popular technique used for reference junction compensation used in data loggers and data acquisition systems is shown in Fig. 13.48.

The measuring junction's terminals are screwed on an isothermal block (the temperature of which remains uniform within ± 0.05 °C). The temperature of the isothermal block is measured independently and compensating voltage is generated using electronic circuitry. This compensation voltage is combined with the emf from measuring junction to obtain the true temperature

Thermocouples are sometimes connected in series or parallel to provide increased voltage or current output.

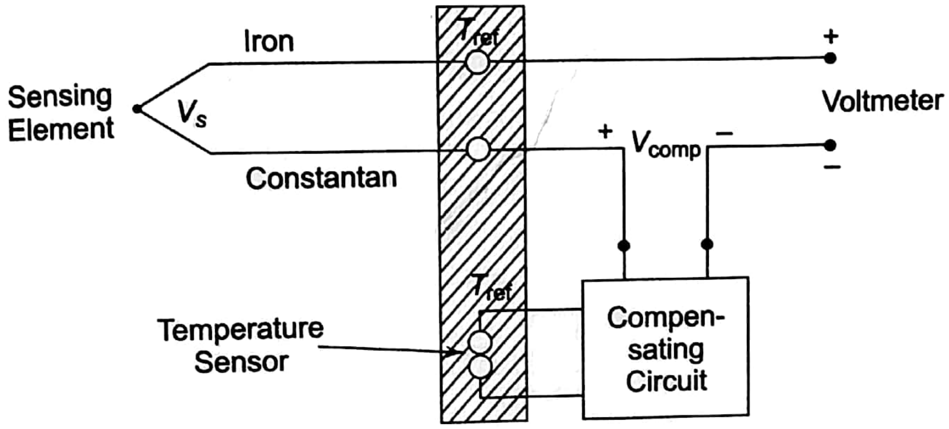
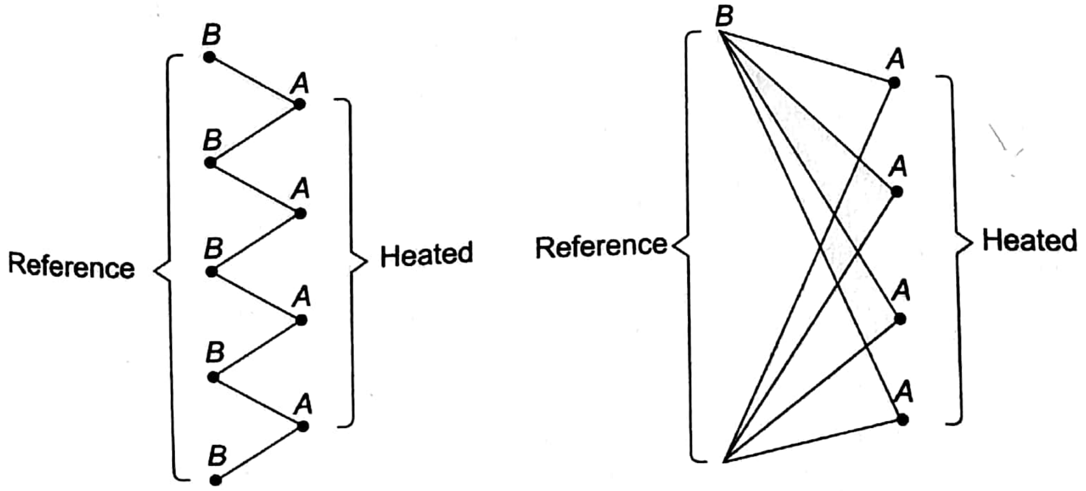


Fig. 13.48 Practical isothermal block reference junction for data loggers, etc.

In Fig.13.49(a), four thermocouples are connected in series, with wire *A* being positive and *B* being negative in each thermocouple.

The total emf between points 1 to 5 is the sum of individual thermocouple emf. An arrangement of this type is called a *Thermopile* and is used to obtain increased sensitivity and greater absolute emf from a thermocouple installation.

Figure 13.49(b) shows four thermocouples in parallel. This arrangement provides a large current but emf is same as that of any one thermocouple.



(a) Series

(b) Parallel

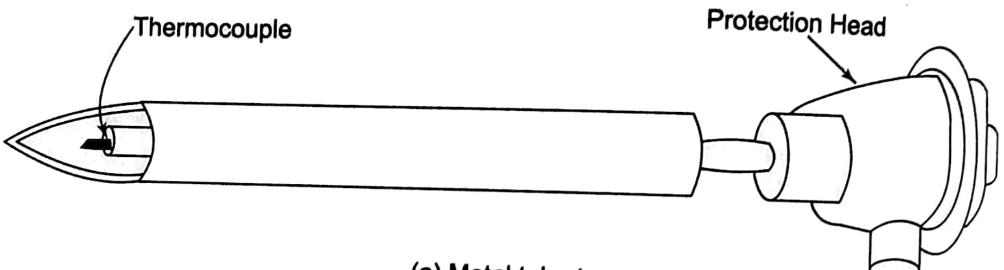
Fig. 13.49 Thermocouples in series and parallel (Thermopile)

Thermocouples must be protected from mechanical damage and isolated from corrosive or contaminating effect that most gases and liquids have at high temperature. The device used for this purpose are called *wells* or *tubes* depending upon their physical construction or *thermowells*.

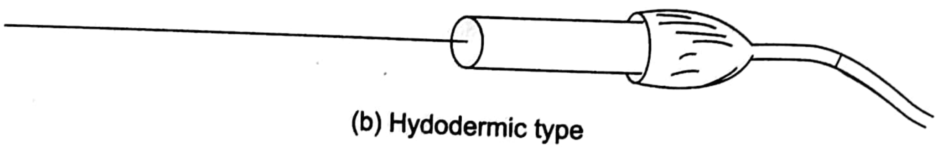
Thermocouples are made from a number of different metal alloys, covering a wide range of temperature from as low as –270 °C (–418 °F) to as high as 2700 °C (about 5000 °F). They may be obtained in a simple uninsulated wire form, in insulated form or inside protective sheaths or probes (sheath diameter as small as 0.25 mm).

The thermo-junction is protected from contamination from the process materials by enclosing it in a protective sheath. For example, a cupro-nickel sheath for copper/chromel thermocouple and mild sheath for iron/chromel thermocouples.

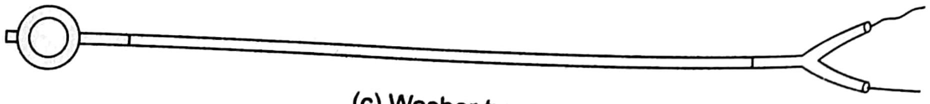
The temperature ranges covered by thermocouples make them appropriate for use in industrial furnaces as well as for measurement in the cryogenic range. Different types of thermocouples are as shown in Fig. 13.50.



(a) Metal tube type



(b) Hydodermic type



(c) Washer type

Fig. 13.50 Different type of thermocouples

Advantages of Thermocouple

1. It has rugged construction.
2. It has a temperature range from –270 °C–2700 °C.
3. Using extension leads and compensating cables, long distances transmission for temperature measurement is possible.
4. Bridge circuits are not required for temperature measurement.
5. Comparatively cheaper in cost.
6. Calibration checks can be easily performed.
7. Thermocouples offer good reproducibility.
8. Speed of response is high compared to the filled system thermometer.

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9. Measur

Disadvantages of

1. Cold ju measure
2. They ex tics.
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13.20.7 Semic

Semiconductor Two of its para current (I_s) are non-linear, but range. Hence, V_f

Fig.13.51

Figure 13.51 silicon pn juncti temperature is af

1. Depende
2. Presence
3. Finite res

The limitation well-matched jun temperature sens

If the two tran the resulting V_{BE} index of tempera

9. Measurement accuracy is quite good.

Disadvantages of Thermocouple

1. Cold junction and other compensation is essential for accurate measurements.
2. They exhibit non-linearity in the emf versus temperature characteristics.
3. To avoid stray electrical signal pickup, proper separation of extension leads from thermocouple wire is essential.
4. Stray voltage pick-up are possible.
5. In many applications, the signals need to be amplified.

13.20.7 Semiconductor Diode Temperature Sensor

Semiconductor diode is a versatile device and finds use in many applications. Two of its parameter, that is forward voltage drop (V_f) and reverse saturation current (I_s) are temperature sensitive. The sensitivity of I_s with temperature is non-linear, but V_f has a linear temperature coefficient over a wide temperature range. Hence, V_f can serve as the basis for electronic thermometers

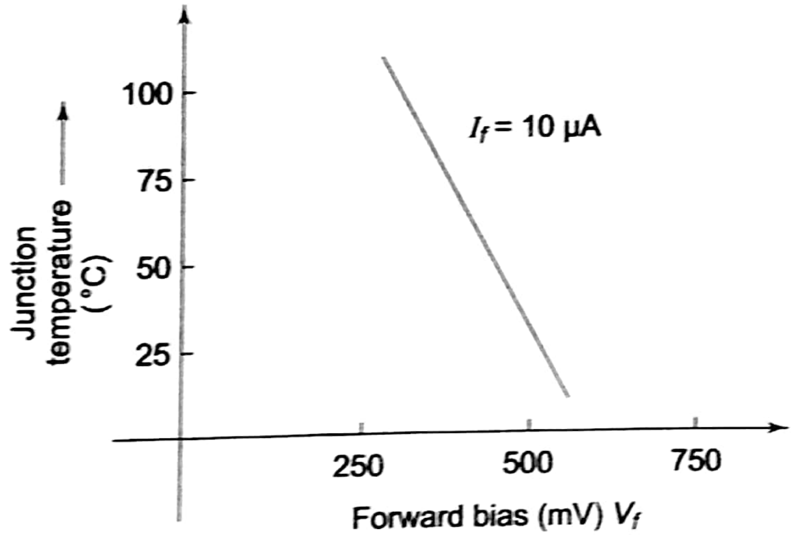


Fig.13.51 Characteristics of forward bias (V_f) versus temperature

Figure 13.51 shows the characteristics of V_f versus temperature for a typical silicon pn junction diode. The linearity of this characteristics at high values of temperature is affected by the following factors.

1. Dependence of V_f on I_s which is also temperature sensitive.
2. Presence of finite surface leakage component across the pn junction.
3. Finite resistance of the bulk semiconductor used for the diode structure.

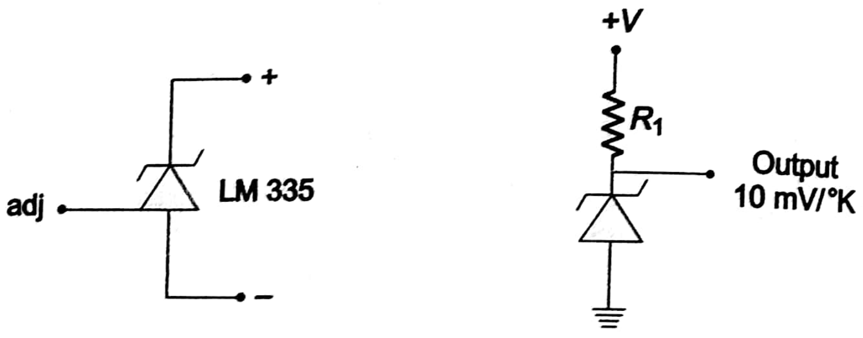
The limitations introduced by point 1 can be overcomed by using a pair of well-matched junction transistors in a differential configuration to serve as the temperature sensors.

If the two transistors are operated at widely different emitter current values, the resulting V_{BE}, Base emitter differential voltage can serve as an excellent index of temperature.

The association of differential mode voltage gain of this stage with V_{BE} provides means of adjusting the temperature coefficient to a desired value. This is the basis of IC type temperature transducer.

13.20.8 IC Type Sensor

IC sensor produces a voltage or current signal that increases with increase in temperature. IC sensors eliminate the linearity errors associated with thermistor. However, being semiconductor devices, they are available in both voltage and current output configuration.



(a) (b)

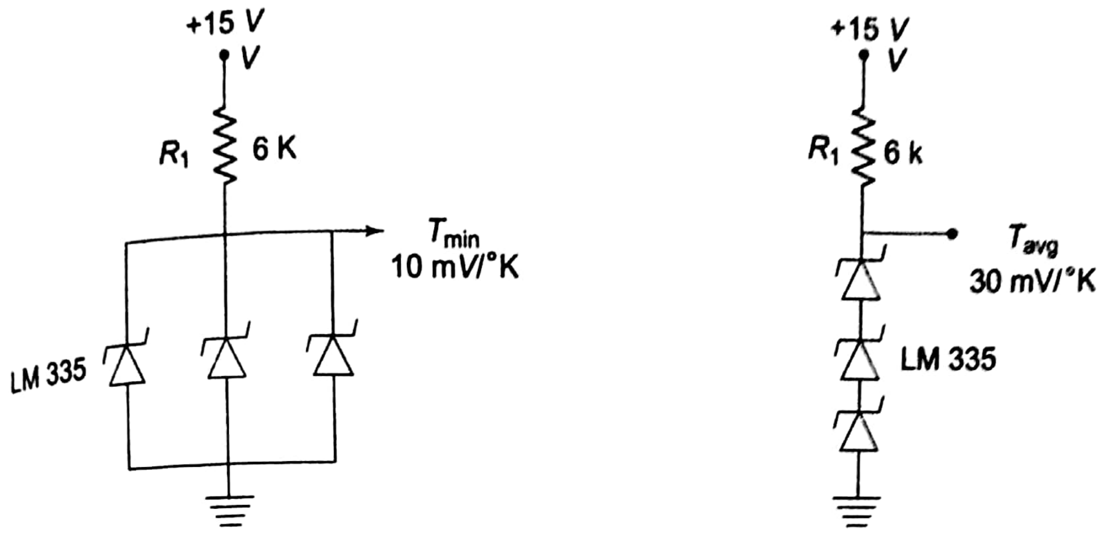
Fig. 13.52 National semiconductor LM 335 IC temperature sensor.

Figure 13.52 shows a National semiconductor LM335 IC temperature sensor. It provides a proportional output of 10 mV/°K. It operates as a two terminal zener. It has a dynamic impedance of less than 1Ω and operates over a current range of 400 μA to 5 mA with virtually no change in performance.

When calibrated at 25 °C, it typically shows less than 1 °C error over a 100° range. Its usable range is –10 °C to +100 °C and LM135 is also available with a range of –55 to 150°C.

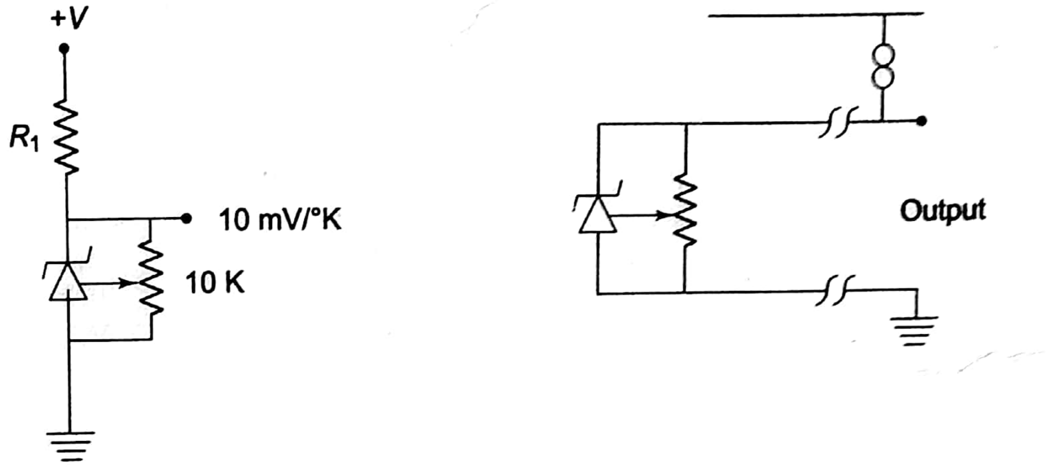
The IC sensor can be used as a minimum temperature sensing circuit, as shown in Fig.13.53(a), because of low dynamic impedance of the sensors. The coolest sensor will set the output voltage. The average circuit using IC sensor shown in Fig.13.53(b) will simply add the individual output voltage. A simple potentiometer circuit used along with the IC sensor provides one point calibration as shown in Fig.13.53(c). The simple point calibration is usually done at the midpoint of the temperature scale. As the output of the IC Sensor LM335 is also available in the form of current source, remote sensing of the temperature using long wire length is also possible as shown in Fig. 13.53(d).

Fabricated on a single monolithic chip, they include a temperature sensor (in the form of a differential pair of transistor), a stable voltage reference and an operational amplifier.



(a) Minimum Temperature Sensing

(b) Average Temperature Sensing



(c) One point calibration (Calibration for 2.982 V at 25°C)

(d) Remote temperature sensor

Figs. 13.53 IC sensor

Using the internal Operational Amplifier (op-amp) with external resistors any temperature scale factor is usually obtained. By connecting the op-amp as a voltage comparator, the output will switch as the temperature crosses the set point making the device useful as an Basic on-off temperature controller as shown in Fig.13.54.

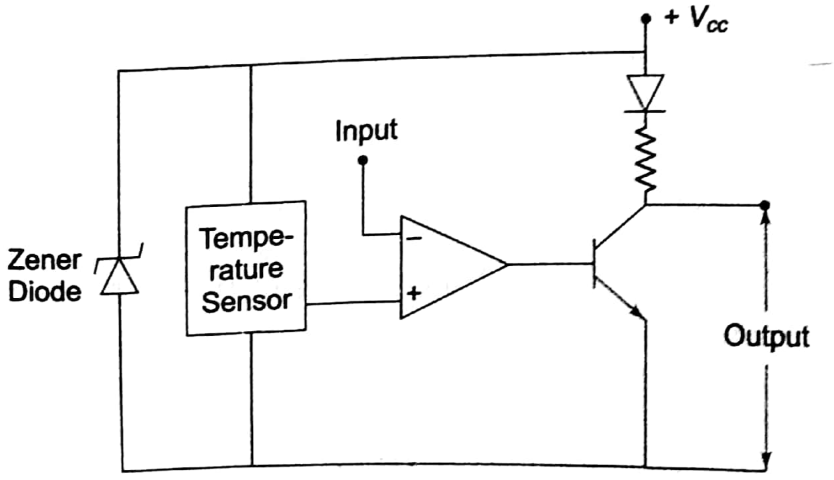


Fig. 13.54 Basic level

13.20.9 Pyrometers

When temperature being measured is very high and physical contact with the medium to be measured is impossible or impractical, optical pyrometers based on the principle of thermal radiation are used. These pyrometers are used under condition where corrosive vapours or liquids would destroy thermocouples, resistance thermometer and thermister, if made to come in contact with the measured medium.

Radiation pyrometers measures the radiant (energy) heat emitted or reflected by a hot object. Thermal radiation is an electro magnetic radiation emitted as a result of temperature and lies in the wavelength of $0.1 - 100\ \mu\text{m}$.

According to the principle of thermal radiation, the energy radiated from a hot body is a function of its temperature. Referring to Fig. 13.55, the heat radiated by the hot body is focused on a radiation detector. The radiation detector is blackened and it absorbs all or almost all radiation falling on it (if the temperature is very small compared with that of hot body, then

$$q = 5.72 \times 10^{-8} \times T^4\ \text{w/m}^2$$

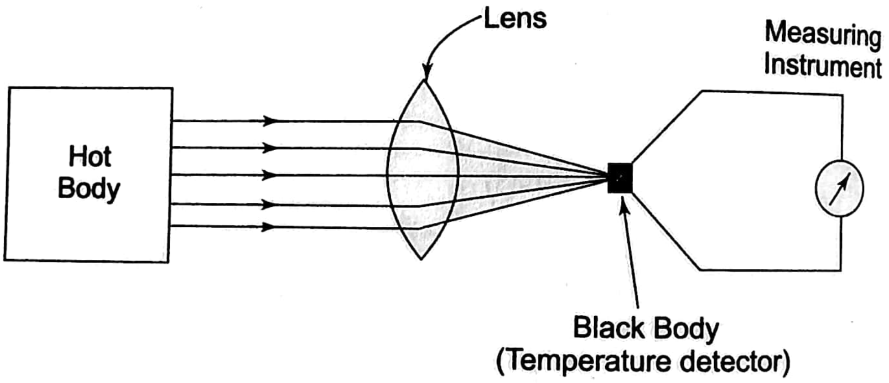


Fig. 13.55 Basic principle of pyrometer

Therefore, the heat received by the detector is proportional to the fourth power of the absolute temperature of the hot body.

Radiation pyrometers are of two types.

1. Total Radiation Pyrometers
2. Infrared Pyrometers

Both of these are discussed in the following sections.

13.20.10 Total Radiation Pyrometer (TRP)

The total radiation pyrometer receives virtually all the radiation from a hot body and focuses on a hot body and focuses on a sensitive temperature transducer such as thermocouple, bolometer, thermopile, etc. Total radiation includes both visible and infrared radiation.

The total radiation pyrometer consists of a radiation receiving element and a measuring device to indicate the temperature directly. Figure 13.56 shows a mirror type radiation pyrometer.

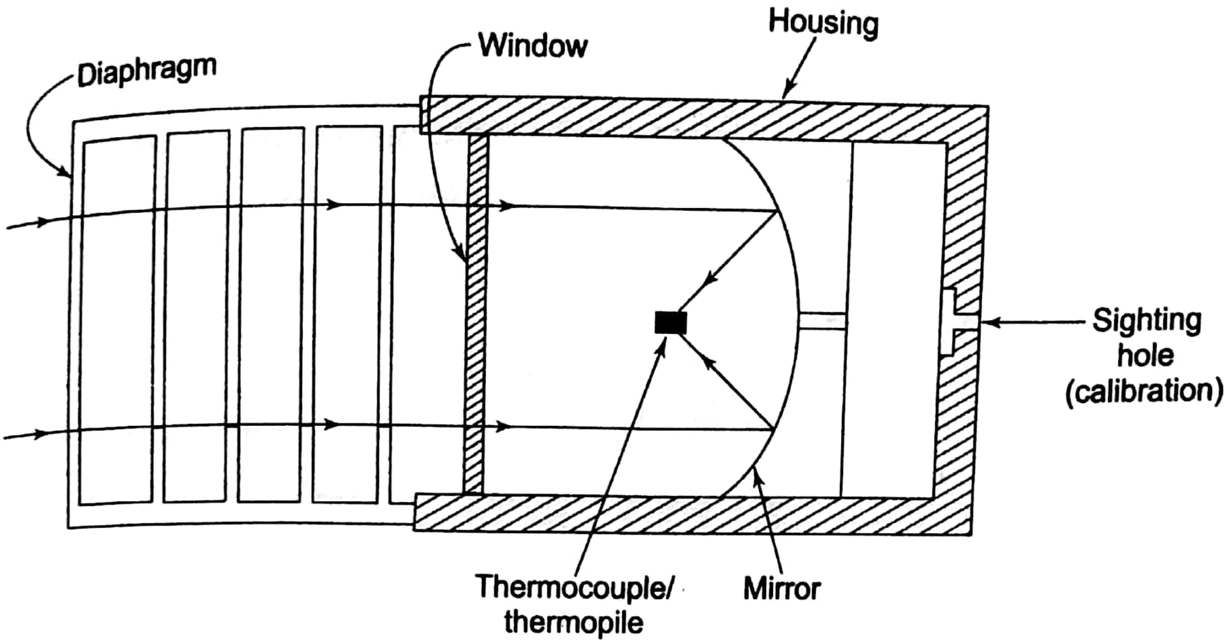


Fig. 13.56 Total radiation pyrometer

In this type of pyrometer, a diaphragm unit along with a mirror is used to focus the radiation on a radiant energy sensing transducers. The lens (mirror) to the transducer distance is adjusted for proper focus. The mirror arrangement has an advantage that since there is no lens, both absorption and reflection are absent.

Presence of any absorbing media between the target and the transducers, reduces the radiation received and the pyrometer reads low.

Due to the fourth Power Law (q is proportional to T^4) the characteristics of total radiation pyrometer are non-linear and has poor sensitivity in lower temperature ranges. Therefore, total radiation pyrometers cannot be used for measurement of temperature lower than 600 °C, since errors are introduced at lower temperatures.

Hence, total radiation pyrometers are used mostly in the temperature range of 1200 °C – 3500 °C.

The output from a total radiation pyrometers whether amplified or not, is usually taken to a PMMC instrument or to a self-balancing potentiometer. The output may be fed to a recorder or controller.

13.20.11 Infrared Pyrometers

Infrared pyrometers are partial or selective radiation pyrometers. Above temperatures of 550 °C, a surface starts to radiate visible light energy and simultaneously there is a proportional increase in the infrared energy.

Infrared principles using thermocouples, thermopile and bolometers are used. Also various types of photo-electric transducers are most commonly used for infrared transducers. The most useful transducers used for industrial application are the Photo-voltaic cells. These cells used in radiation pyrometers, respond to wavelength in infrared region and may be used to measure temperature down to 400 °C.

The infrared radiation is focused on a photo-voltaic cell as shown in Fig. 13.57. It is necessary to ensure that the cell does not become overheated. The core of radiation passing to the cell is defined by the area of the first diaphragm.

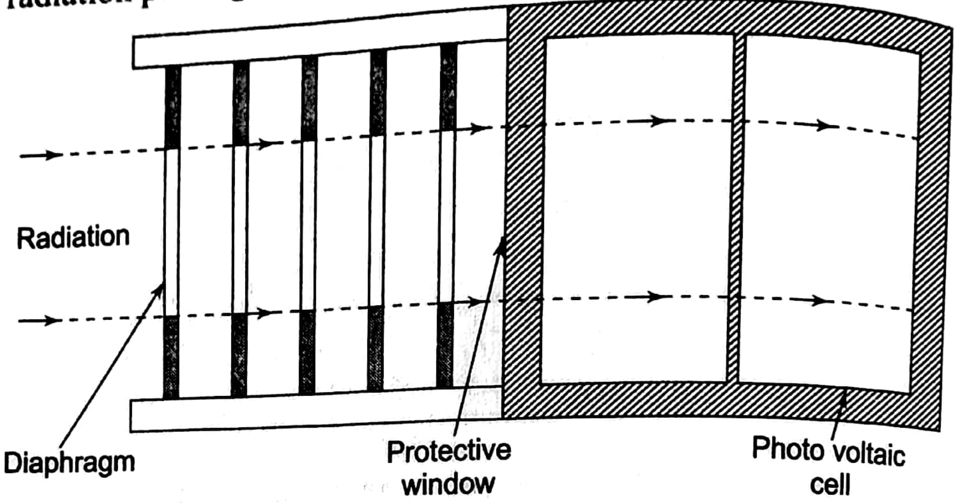


Fig. 13.57 Infrared pyrometer

The protective window is made of thin glass and serves to protect the cell and filter from physical damage. The filter is used on the range of 1000 °C to 1200 °C in order to reduce the infrared radiation passed to the photo cell. This help in preventing the photo cell from being overheated.

All infrared systems depend on the transmission of the infrared radiant energy being emitted by a heated body to a detector in the measuring system. The sensor head is focused on the object whose temperature is being measured and/or controlled.

The infrared energy falling on the detector either changes the detector resistance in proportion to the temperature as in the case of thermister or generates an emf in the detector such as a thermopile. The change in resistance or generated emf is then indicated on a meter.

13.20.12 Optical Pyrometer

Any metallic surface when heated emits radiation of different wavelengths which are not visible at low temperature but at about 550 °C, radiations in shorter wavelength are visible to eye and from the colour approximate temperature is measured. The approximate values of temperature for colour (colour scale) is given in Table 13.4.

Table 13.4 Colour scale

Dark Red	540°C
Medium Cherry Red	680°C
Orange	900°C
Yellow	1010°C
White	1205°C

The radiations from a heated body at high temperature fall within the visible region of the EM spectrum. For a given wavelength in the visible region the energy radiated is greater than at higher temperature.

Within a visible range, a given wavelength has a fixed colour and the energy of radiation is interpreted as Intensity or Brightness. Hence if we measure the brightness of the light of a given colour emitted by a hot source, we have an indication of temperature. This is the principle of optical pyrometer.

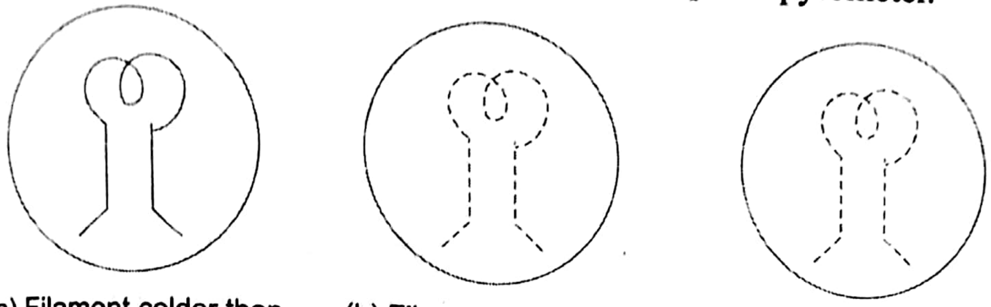

(a) Filament colder than background
(b) Filament invisible against background
(c) Filament and background having equal brightness

Fig. 13.58

In an optical pyrometer, the wavelength of radiation accepted is restricted by means of a colour filter and brightness is measured by comparison with a standard lamp.

The most common type of optical pyrometer used is the disappearing filament pyrometer. The schematic is shown in Fig.13.59.

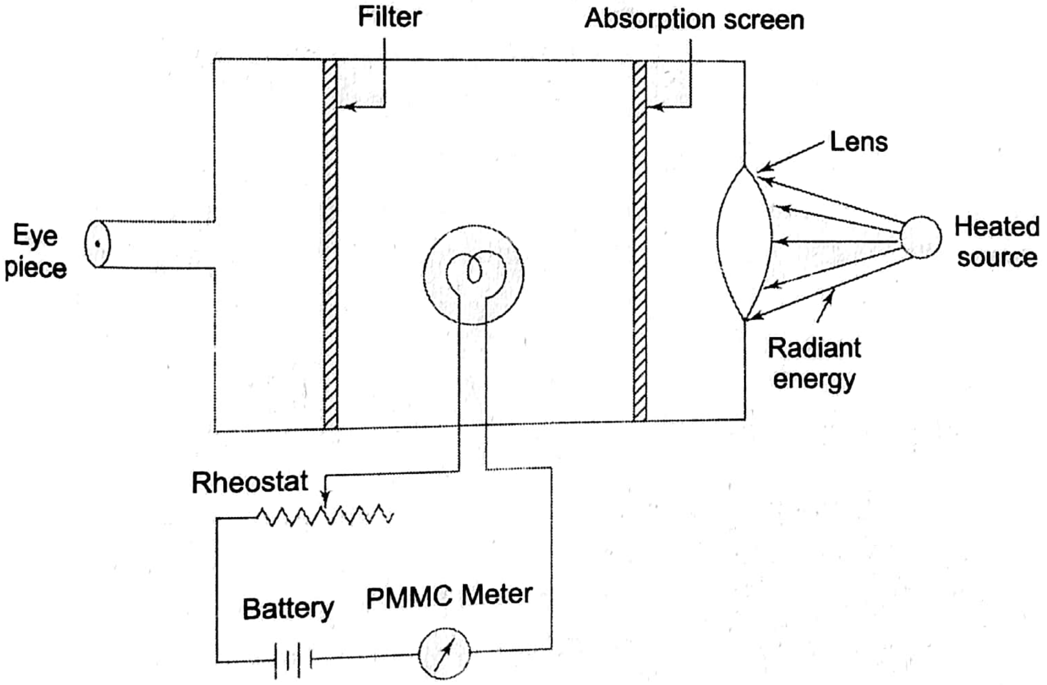


Fig. 13.59 Optical pyrometer

An image of the radiating source is produced by a lens and made to coincide with the filament of an electric lamp.

The current through the lamp filament is made variable so that the lamp intensity can be adjusted. The filament is viewed through an eye piece and filters. The current through the filament is adjusted until the filament and the images are of equal brightness.

When brightness of image produced by the source and brightness produced by the filament are equal, the outline of the filament disappears as shown in Fig.13.58(c).

However, if the temperature of the filament is higher than that required for equality of brightness, filament becomes too bright as shown in Fig.13.58(b).

On the other hand if the temperature of filament is lower, the filament becomes dark as shown in Fig.13.58(a).

Since the intensity of light of any wavelength depends upon the temperature of the radiating body and the temperature of filament depends upon the current flowing through the lamp. The instrument may be directly calibrated in terms of the filament current. However, the filament current depends upon the resistance of the filament, modern pyrometers are calibrated in terms of resistance directly.

The range of temperature, which can be measured by an instrument of this type depends on the maximum allowable temperature of the lamp which is around 1400 °C.

The range can be extended by using an absorption type screen placed near the objective lens. Hence a known fraction of radiant energy enters the pyrometer for comparison. The range can be extended to 3000 °C by this technique.

Optical pyrometers is widely used for accurate measurement of temperature of furnaces, molten metals and other heated materials.

13.20.13 Ultrasonic Temperature Transducer

Ultrasonic transducers (sound vibrations above 20 kHz) are useful when we are concerned with rapid temperature fluctuations, temperature extremes, limited access, nuclear or other severe environmental requirements and measurement of temperature distribution inside solid bodies.

They may be used to measure the distribution of parameters other than temperature (example flow). Ultrasonics also offers possibilities of remote sensing.

Ultrasonic thermometer sensors permit one to measure an extremely wide range of temperatures, from cryogenic to plasma levels and to achieve micro to milli-second response time, milli-degree resolution, greater choice of materials for sensors, operation in nuclear or corrosive environment and remote location of transducer.

Using ultrasonics for profiling permits one to obtain 2 – 10 or more temperatures using a single transmission line. This feature simplifies installation and provides reliable, accurate data at a reasonable price.

FREQUENCY GENERATING TRANSDUCER 13.21

Unlike variable parameter analog transducers, frequency and pulse generating transducers measure physical variables in terms of a pulse repetition rate.

Since frequency is an analog quantity, these can be treated as either analog or digital devices. Therefore, any phenomenon to be measured is converted into a corresponding rate of pulse generation which undergoes counting process and is made digital in nature.

These transducers produce a simple series of voltage or current pulses or cycles in proportion to the change in the physical parameter being measured. The series of pulses can be counted over a certain precisely determined period of time and the input magnitude can be known with considerable accuracy.

Examples of such devices are pulse generating pick ups operating on the variable reluctance principle, photo-tubes, etc.

RELUCTANCE PULSE PICK-UPS 13.22

This transducer is very suitable for the measurement of shaft speed and liquid flow. It is based on the principle that if the field of any magnet is varied momentarily by the motion of an external magnetic body near it, a voltage pulse is generated at the coil of the magnet because of the change in flux surrounding the coil. The transducer consists of a permanent magnet on which a coil is wound. The output voltage depends upon the rate of change of magnetic flux and the number of turns. Flux depends upon the clearance between the pick up and the actuating medium, the rate of movement and size of the actuating medium. The output voltage is inversely proportional to the distance between the head of the pick up and the actuating medium.

The pick up is actuated by the teeth of a gear or blades of turbines. In rpm measurement, the pick up is placed near the teeth of a gear. The motion of the gear tooth distorts the magnetic field around the core magnet.

A voltage pulse is produced every time a tooth enters or leaves the area of the pick up coil. The frequency of pulse is then proportional to the speed of the gear. This can be used for a tachometer.

Similarly, a pick up can be used to determine the flow, as the speed of the turbine through which the liquid flows is proportional to the flow. The total pulses counted are proportional to the total flow.

FLOW MEASUREMENT (MECHANICAL TRANSDUCERS) 13.23

The measurement of flow rate and quantity is the oldest of all measurements of process variables in the field of instrumentation. It is used to determine the amount of materials flowing in or out of a process.

Without flow measurements, plant material balancing, quality control and the operation of any continuous process would be impossible. Flow velocities are also measured by inductive transducers. The measurement of liquids containing suspended solids, such as sewage or feed to paper mills, present considerable problems. This is overcomed by the use of a flowmeter.

The transducer can be used to measure the flow of any flowing material that is electrically conductive. (The meter can be regarded as a section of pipe that is lined with an insulating material.)

Two saddle coils are arranged opposite each other and electrodes diametrically opposite are arranged flush with the inside of the lining. If the coils are energised the moving liquid, (as a length of conductor) cuts the lines of force, resulting in the generation of an electromotive force that is picked up by the electrodes. By suitable circuitry and amplification, an electrical signal proportional to the flow can be obtained.

Many accurate and reliable methods are available for measuring flow, some of which are applicable only to liquids, some only to gases and some others to both. Fluids measured may be clear or opaque, clean or dirty, wet or dry, erosive or corrosive. Fluid streams may be multiphase, vapour, liquid or slurries. The flow may be turbulent or laminar, and viscosity and pressure may vary from vacuum to many atmospheres. Temperature may range from cryogenic to hundreds of °C.

Flow rate may vary from a few drops per hour to thousands of gallons per minute.

MECHANICAL FLOW METER

13.24

In mechanical flow meters, there is a mechanism in the path of the flow which moves continuously at a speed which is proportional to the flow rate. These are generally used for metering liquids however with certain modifications, they can be designed to meter gases also. They can be divided into two main categories, with further subgroups.

1. Displacement type
2. Inferential type

The displacement type are volumetric in operation, the cyclic displacement of the detecting element, e.g. piston, being directly proportional to the volume of the fluid passing through the meter during each cycle.

Inferential type flow meters are current type flow meters are measure the velocity of flow, from which the volume of flow is inferred.

MAGNETIC FLOW METERS

13.25

Magnetic flow meters are the first type of flowmeters to be considered for high corrosive applications and for applications involving measurement of erosive slurries. These meters work on the principle of Faraday's law of electromagnetic induction, which states that whenever a conductor moves through a magnetic field of given field strength, a voltage is induced in the conductor proportional to the relative velocity between the conductor and the magnetic field. This concept is used in electric generators. In case of flowmeters, electrically conductive flowing liquids work as the other conductor. The induced voltage is given by the equation

$$E = C \times B \times L \times V \tag{13.17}$$

where E = Induced voltage in volts
C = Dimensional constants
B = Magnetic flux in Wb/sq.m
L = Length of the conductor (fluid) in m
V = Velocity of the conductor (fluid) in m/s

The equation to convert a velocity measurement to volumetric flow rate is

$$Q = V \times A \tag{13.18}$$

where Q = Volumetric flow rate
V = Fluid velocity
A = Cross-sectional area of the flowmeter

From (13.17)

$$V = \frac{E}{CBL}$$

Therefore

$$Q = \frac{EA}{CBL}$$

For a given flowmeter, A, C, B, L are constants.

Therefore

$$Q = K \times E \qquad \text{where } K = \frac{A}{CBL} \tag{13.19}$$

Therefore the induced voltage is directly proportional and linear to the volumetric flow rate.

Construction The magnetic flow meter consists of an electrically insulated or non conducting pipe, such as fibre glass, with a pair of electrodes mounted opposite each other and flush with the inside walls of the pipe, and with the magnetic coil mounted around the pipe so that a magnetic field is generated in a plane mutually perpendicular to the axis of the flow meter body and to the plane of the electrodes.

If a metal pipe is used, an electrically insulating liner is provided on the inside of the pipe.

The basic operating principle of a magnetic flowmeter in which the flowing liquid acts as a conductor is shown in Fig. 13.60.

The length L is the distance between the electrodes and equals the pipe diameter. As liquid passes through the pipe section, it also passes through the magnetic field set up by the magnet coils, thus inducing a voltage in the liquid, which is detected by a pair of electrodes mounted on the pipe wall. The amplitude of the induced voltage is proportional to the velocity of the flowing liquid. The magnetic coils may be excited by either ac or dc voltage. Currently, pulsating dc in which magnetic coils are periodically energised is used.

Magnetic flow meters are available in sizes from 2.54 – 2540 mm in diameter, with an accuracy range of ± 0.5 to ± 2%. The measurement taken by these meters are independent of viscosity, density, temperature and pressure. (The range of such meters may be 30 :1, but normally a 20:1 range is accepted.)

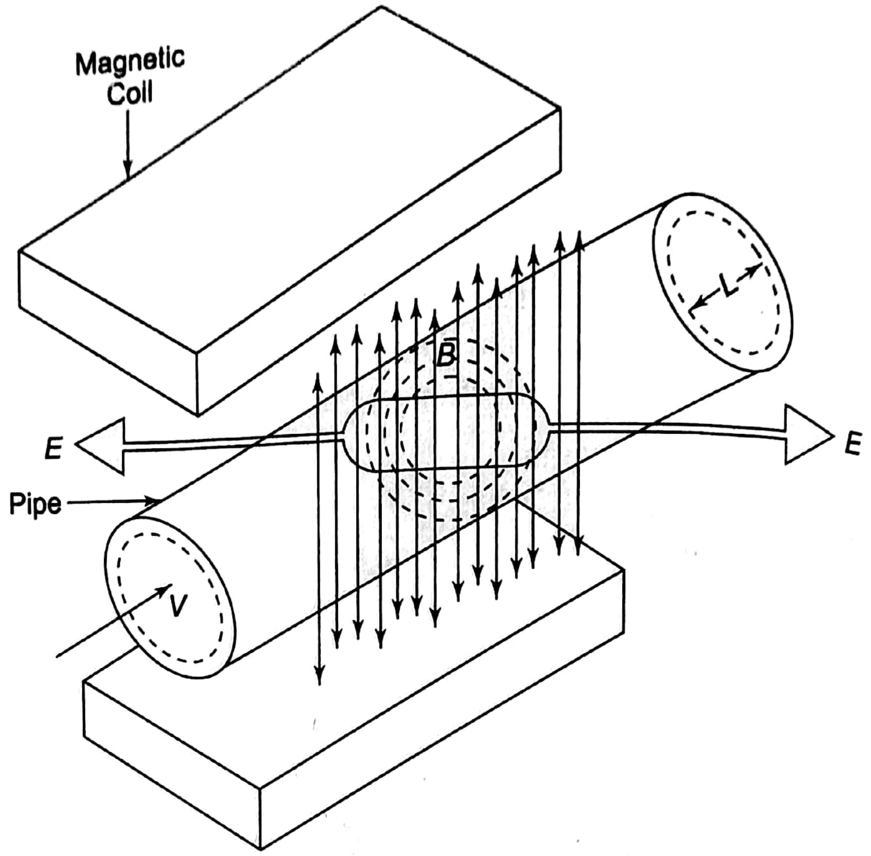


Fig. 13.60 Working principle of magnetic flowmeter

A modern design of magnetic flowmeter is one which can be inserted into the line through couplings. It consists of electrodes mounted on each side of a probe and magnetic coils which are also integral to the probe. The probe can be mounted on pipes of diameters 152.4 mm and above can easily be mounted for open channel flow.

Advantages of Magnetic Flowmeter

1. It can handle slurries and greasy materials.
2. It can handle corrosive fluids.
3. It has very low pressure drop.
4. It is totally obstructionless.
5. It is available in large pipe sizes and capacity as well as in several construction materials.
6. It is capable of handling low flows (with minimum size, less than 3.175 mm inside diameter) and very high volume flow rate (with sizes as large as 3.04 m).
7. It can be used as bidirectional meter.

Disadvantage of Magnetic Flowmeter

1. It is relatively expensive.
2. It works only with fluids which are adequate electrical conductors.
3. It is relatively heavy, especially in larger sizes.
4. It must be full at all times.
5. It must be explosion proof when installed in hazardous electrical areas.

TURBINE FLOWMETER

13.26

The turbine flowmeter is used for the measurement of liquid gas and gases of very low flow rate. It works on the principle of turbine. It consists of a multibladed rotor (called turbine wheel) which is mounted 90° to the axis of the flowing liquid as shown in Fig. 13.61.

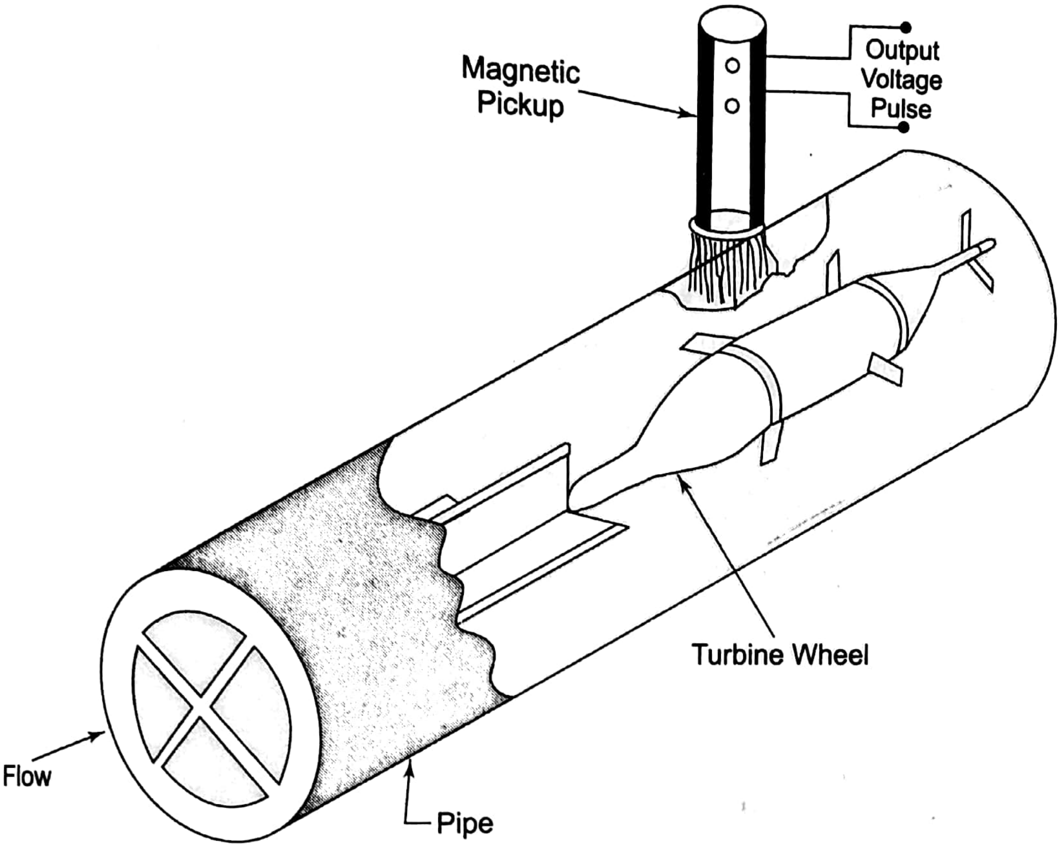


Fig. 13.61 Turbine flowmeter

The rotor is supported by the ball or sleeve bearings on a shaft which is retained in the flow meter housing by a shaft support section. The rotor is free to rotate about its axis.

The flowing liquid strikes the turbine blades (rotor) imparting a force to the blade surface which causes the rotation of the rotor. At a steady rotational speed, the speed of the rotor is proportional to the fluid velocity and hence to the volumetric flow rate. The speed of rotation is monitored by a magnetic pick up which is fitted to the outside of the meter housing.

The magnetic pick-up coil consists of a permanent magnet with coil windings which is mounted in close proximity to the rotor but internal to the fluid channel. As each rotor blade passes the magnetic pick-up coil, it generates a voltage pulse which is a measure of the flow rate. The total number of pulses gives a measure of the total flow.

The electrical voltage pulses produced can be totalled, differenced or manipulated by digital techniques, so that a zero error characteristic, using this technique, is provided from the pulse generator to the final read.

The number of pulses generated per gallon of flow, called the *K* factor is given by

$$K = \frac{T_k f}{Q} \tag{13.20}$$

where K = pulses per volume unit
T_k = time constant in minutes
f = frequency in Hz
Q = volumetric flow rate is gpm (gallon per minute)

Turbine flow meters provide very accurate flow measurement over a wide flow range. The accuracy range is ± 0.25 to ± 0.5% with excellent repeatability, i.e. precision ranging from ± 0.25% to as good as ± 0.02%.

The range of turbine meters is generally between 10 : 1 and 20 : 1; however, in a low flow rate it is less than 10 : 1.

Military turbine meters have a range greater than 100 : 1.

Turbine meters are available in different sizes, ranging from 6.35 – 650 mm and liquid flow ranges from 0.1 – 50 000 gallons per minute.

These turbine flow meters are mostly used for military applications. They are also used in blending systems in the petroleum industry. They are effective in aerospace and airborne applications for energy fuel and cryogenic (liquid oxygen and nitrogen) flow measurements.

Advantages of Turbine Flowmeter

1. Good accuracy
2. Excellent repeatability and range
3. Fairly low pressure drop
4. Easy to install and maintain
5. Good temperature and pressure ratings
6. Can be compensated for viscosity variations

Disadvantages

1. High cost (expensive)
2. Limited use for slurry applications
3. Problems caused by non-lubricating fluids

MEASUREMENTS OF THICKNESS USING BETA GAUGE 13.27

A common and characteristic feature of a radioactive element is that they disintegrate spontaneously to produce fresh radioactive elements called daughter elements. This activity of parent elements is termed as radioactivity.

During this disintegration, high energy radiations are emitted from the nuclear of the radioactive element. These high energy radiations are mostly of three types: the positively charged rays called alpha (α) rays, the negatively charged rays called beta (β) rays, and the neutral rays called gamma (γ) rays. β rays are usually, but not necessarily accompanied by (γ) rays.

Some of the basic and important properties of α, β, and γ-rays are listed in Table 13.5.

Table 13.5

1. Alpha (α) ra

2. Beta (β) ray

3. Gamma (γ)

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Table 13.5

1. Alpha (α) rays	(a)	They consists of positively charged particles.
	(b)	They are emitted from the nucleus of a radioactive atom with a high velocity.
	(c)	They possess high energies.
	(d)	Since α-particles produce intense ionisation, they lose energy quickly and are therefore, stopped within a short distance.
	(e)	Since they carry a positive charge, they can be deflected by electric and magnetic fields.
2. Beta (β) rays	(a)	They consists of negatively charged particles.
	(b)	They are emitted from the nucleus of radioactive atoms with very high velocities.
	(c)	They possess less energies as compared to α-rays.
	(d)	Since they produce only moderate ionisation, they do not lose energy very rapidly.
	(e)	As they carry a negative charge, they can be easily deflected by electric and magnetic fields.
3. Gamma (γ) rays	(a)	They are not made up of any charged particles at all.
	(b)	They are emitted from the nucleus of radioactive atom as high energy photons, i.e. they are electromagnetic waves of very short wavelength.
	(c)	Since they produce only feeble ionisation, they do not loose energy very fast.
	(d)	Since they do not carry any charge, they cannot be deflected by electric or magnetic fields.

Alpha rays are not used in radiometrical measurement techniques because their range is only some mm, even in air. Hence this leaves only beta and gamma radiations.

Measuring Principle The measurement of the $\dfrac{\text{weight}}{\text{unit area}}$ of the sheet material is accomplished by measuring the absorption of radiation emanating from a radio isotope when passing through the material. If the material is homogeneous and its density is known, the wt/unit area measurement can be transformed into a thickness measurement.

Mode of Operation Figure 13.62 shows a schematic block diagram of a beta gauge.

The source (1), enclosed in a source holder, is positioned to one side of the material to be measured (2) The measuring chamber (3), containing an ionisation chamber as the detector, is located exactly opposite the source, on the other side of the material. Part of the radiation from the source is absorbed during the passage through the material, and the remaining radiation ionises the gas in the ionisation chambers. A dc converter (5) supplies the anode of the ionisation chamber with high voltage. The resulting field causes an ionisation current I_x proportional to the intensity of the received radiation. This current is collected by the measuring electrode.

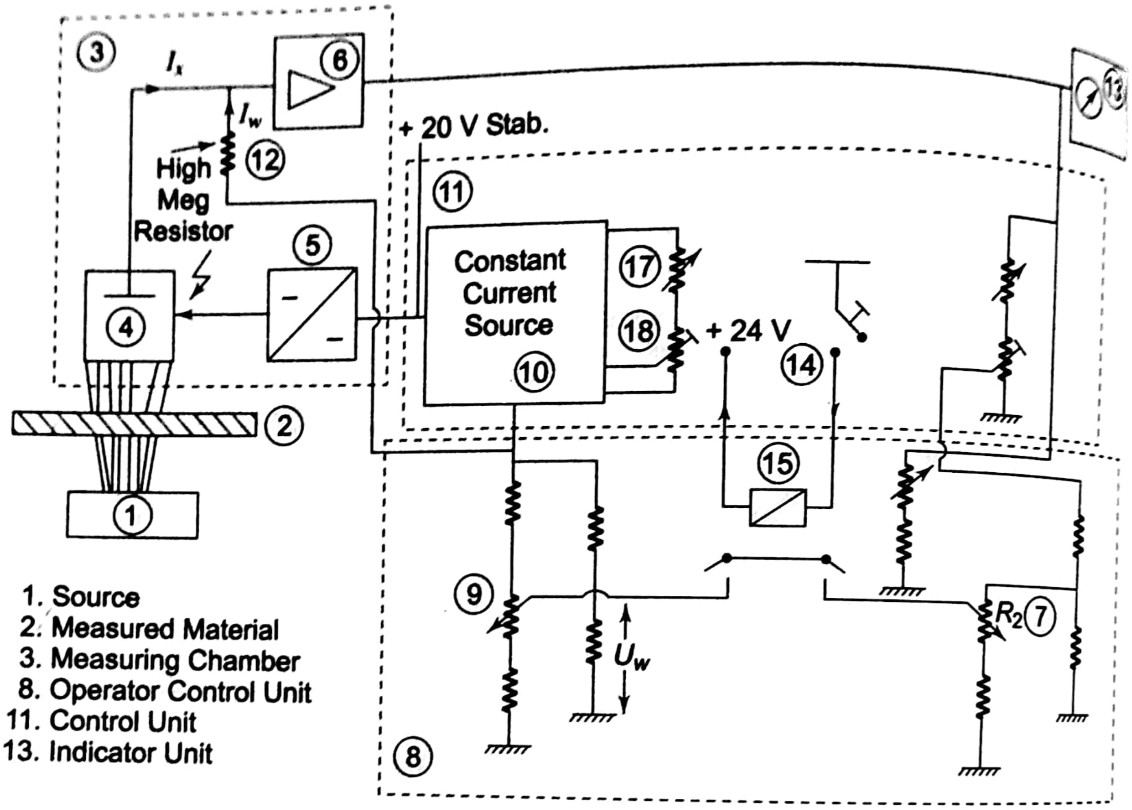

Fig. 13.62 Schematic block diagram of a beta gauge

The capacitor-diode amplifier (6), is a dc amplifier with high input impedance and low leakage. In its feedback loop, the voltages from the feedback divider (7), located in the operator control unit (8) and the target value adjust (9), are effective. The target value adjust is calibrated such that the voltage applied to the high-meg resistor of the measuring chamber causes a current I_w equal and opposite in polarity to the ionisation current I_x. If the measured wt/unit area or thickness of the material in the measuring gap is on target, the voltage at the amplifier output connected to the deviation indicator input goes to zero.

Deviations of the measured product from the target cause the indicator to move towards plus or minus proportional to the magnitude of the error.

Full radiation is used for balancing the system, i.e. no material in the measuring gap. By pushing the full radiation button (14) in the control unit (11), the feedback loop is connected via a relay (15) to a compensation voltage equivalent to zero weight or no material (product) in the measuring gap. The deviation indicator (13) should be moved to zero by actuating the coarse switch and adjusting the fine potentiometer. This adjusts both the feedback voltage and current I_w to match the ionisation current.

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Measuring Chamber The measuring chamber is utilised for measuring base weight or thickness by absorption of radioactive radiation.

It is dust tight, with ambient temperature ranges from + 10°C – +50 °C. The influence of the temperature of the air in the measuring gap on the measurement is compensated for by the temperature compensation circuit. The ionisation current causes a voltage drop across the high-meg resistors. The difference between this voltage drop and the compensation voltage is amplified by a two-stage capacitor-diode amplifier.

Control Unit The control unit supplies the voltage for the measuring chamber. It contains the master switch and the elements for balancing are equipped with automatic temperature compensation, i.e. compensation of wt/unit area caused by temperature changes of the air in the measuring gap.

This system requires the following voltages: 24 V ac and +24 V dc stabilised. 24 V ac is tapped from a separate winding of the power transformer. A separate winding also supplies the circuit protected stabilised power supply + 24 V dc and 0.7 A.

A constant current source supplies the operator control unit. The target value potentiometer in this unit sets the comparator voltage for the measuring chamber. Since the constant current source must be floating, an electronic chopper is employed to supply its regulator.

The temperature compensation circuit, if supplied, adjusts for temperature related changes of wt/unit area of the air in the measuring gap. It does this by feeding an error voltage to the constant current source. This voltage is generated by an IC amplifier in a bridge circuit one of whose branches contains temperature sensors (NTC) of the measuring chamber and the source holder.

Balancing, i.e. compensation for a source decay, is accomplished by adjusting the constant current and the feedback voltage derived from the measured value to match the compensation voltage of the measuring chamber proportional to the source decay.

13.27.1 Control Sequence of the Motion of the Measuring Heads

The control of the measuring head motion is possible in various program sequences such as (i) automatic profile scanning, (ii) traversing scanning, (iii) jugging, (iv) off-sheet position, and (v) test position.

1. Automatic Profile Scanning After pressing the profile push button, the measuring head leaves the off-sheet position E_a, as shown in Fig. 13.63, passes the limit switch at the left side sheet edge E_b and stops at the permanent measuring position E_d. Presetting this button again, or after making contact with the preset time switch mechanism initiates the automatic profile scanning. The measuring head moves at high speed to the right side E_r, then back to the left side edge at low speed and returns at high speed to the center positions E_d. It records only at low speed.

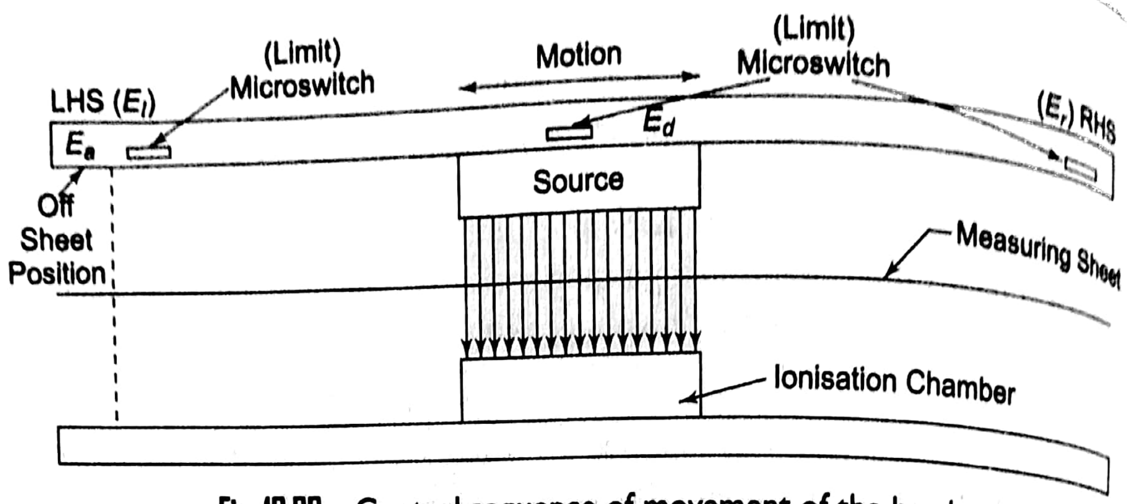

Fig. 13.63 Control sequence of movement of the head

2. Traversing This program constitutes a pendular movement of the measuring head, between two limit switches E_l and E_r, whereby the traversing speed from the right side to the left side can be determined by converting the bridges, released by pressing the traverse button.

3. Jugging At jugging, an optimal positioning of the measuring head between the limit switches E_a and E_r is possible.

4. Off-sheet Movement Off-sheet movement to the limit switch E_a can be effected by various command inputs, either by pressing the push-button off-sheet movement at the control panel, or by means of the adjustment command from the power supply unit.

5. Test Position This limit switch is situated outside the right side turning point E_r and can be reached by the Test Position button.

Review Questions

1. Define a transducer.
2. Explain the difference between primary sensors and transducers with the help of examples.
3. With the help of examples, explain the procedure of converting displacement response of some primary sensors into electrical output.
4. What do you understand by electrical transducers? State the advantages of an Electrical transducer.
5. State the various parameters of electrical transducers.
6. List five physical quantities that the transducer measures.
7. List different types of transducers.
8. List the factors to be considered while selecting a transducer.
9. Explain the difference between primary sensors and transducers with the help of examples.
10. What is the difference between passive and active transducers.
11. Differentiate between primary and secondary transducers.
12. Explain with diagram the functions of a resistive transducer.
13. Explain with diagram potentiometer used as a transducer.
14. Describe with the help of a diagram, the measurement of displacement using potentiometers. State the